UNIVERSITY OF
MARYLAND

3 National Transportation Center

Project ID: NTC2016-SU-R-2

EFFECT OF PAVEMENT CONDITION ON ACCIDENT RATE

Final Report

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June 2017

ACKNOWLEDGEMENTS

This project was funded by the National Transportation Center @ Maryland (NTC@Maryland), one of the five National Centers that were selected in this nationwide competition, by the Office of the Assistant Secretary for Research and Technology (OST-R), U.S. Department of Transportation (US DOT). The cost share contributed by Arizona State University is greatly appreciated. Appreciation is also given to transportation engineers in Arizona, Maryland and North Carolina for answering queries and providing data used in this study.

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EXECUTIVE SUMMARY

Highway safety is a major priority for the public and for transportation agencies. Pavement distresses directly affect ride quality, and indirectly contribute to driver distraction, vehicle operation, and accidents. In this study, analysis was performed on highways in the states of Arizona, North Carolina and Maryland for the years between 2013 and 2015 to investigate the relationship between accident rate and pavement ride quality (roughness) and rut depth. Two main types of data were collected: crash data from the accident records and International Roughness Index (IRI) and rut depth data from the pavement management system database in each state. Crash road segments represented 37-48 percent of the total length of the network using 1-mile segments. IRI and rut depth values for crash and non-crash segments were close to each other, suggesting that roughness and rutting are not the only factors affecting number of crashes but possibly in a combination with other factors such as traffic volume, human factors, etc. Crash rates were calculated using the U.S. Department of Transportation method, which is the number of accidents per vehicle per mile per year multiplied by 100 million. The variations of crash rate with both IRI and rut depth were investigated. Sigmoidal function regression analysis was performed to study the relationship between crash rate and both IRI and rut depth. In all cases, the crash rate did not basically increase up to a critical IRI value of 210 inches/mile or a critical rut depth value of 0.4 inches. When the IRI or rut depth increased above these critical values the crash rate largely increased. This is a key conclusion that provides empirically derived thresholds for safety concerns. If transportation agencies keep their road network below these critical pavement conditions, the crash rate would largely decrease. In summary, it can be concluded that both ride quality and rut depth affect crash rate and highway maintenance authorities need to maintain good pavement conditions in order to reduce crash occurrences.

1.0 INTRODUCTION

1.1 Background

Accident statistics developed by the U.S., state and local Departments of Transportation show that when a large number of accidents occurs there are notable implications on the economy (Blincoe, 2015). Several factors affect the accident rate such as human factors, vehicular causes, environment, roadway geometry, traffic volume, pavement condition, and their combinations. Studies show that the majority of accidents are caused by human factors such as distraction, alcohol, stress, physical deficiency and age (Garber, 2015). Although pavement condition is not a major factor that affects accidents, maintaining good pavements would likely reduce the accident rate. On the other hand, people might argue that when the pavement condition is poor, drivers tend to be more cautious and reduce speed, which in turn might reduce the crash rate.

Pavement distresses directly affect ride quality, and indirectly contribute to driver distraction, vehicle operation, and accidents (Quinn 1972, TRB 2009). For example, a pavement with a bad record of roughness or potholes can cause a vehicle to lose control when braking or turning, especially under adverse environmental conditions (Figures 1.1). When pavement roughness increases, the contact area between vehicle tires and pavement decreases, resulting in lower brake friction. Also, roughness can contribute to greater vehicle instability since different friction forces may exist on the two sides of the vehicle.

Figure 1.1. Poor pavement condition may contribute to driver distraction, substandard vehicle operation and accidents (http://www.carprousa.com/bumpy-commute-try-driving-on-fords-pothole-road)

Another type of pavement distress that may affect accident rate is rutting (Figure 1.2). Rutting acts along a wheel path, and may result in a driver needing to exert extra effort to get out from the wheel path (if the rut depth is large), thus leading to uncertain and in some cases uncontrolled lateral vehicle movement. Moreover, rutting is more hazardous in wet weather when water accumulates in the rut path and leads to hydroplaning and loss of control. The problem can be further exaggerated when human factors, such as distraction, alcohol, stress, physical deficiency and age, are combined with pavement distresses.

Figure 1.2. Example of pavement rutting (http://www.qespavements.com/node/113)

The effect of pavement condition, other than friction, on crash rate is typically not straight forward. Although pavement roughness and rutting may cause driver distraction, these distresses might make drivers more cautious and tend to reduce speed, and consequently may reduce accident potential. Also, since accidents are typically caused by a combination of factors, the problem might be confounded and roughness or rutting by itself may not show direct correlation with accident rate. For example, an accident could be caused by heavy traffic, poor visibility, and poor roughness combined. Therefore, accident studies should consider all factors involved and their combinations, not just one factor at a time.

Transportation agencies try to improve roadway safety through proper pavement engineering and maintenance in order to improve their economic competitiveness. The majority of the studies dealing with the effect of pavement condition on safety are related to skid resistance, and not roughness or riding quality (Blackburn, 1978; Hall, 2009; Kuttesch, 2004; Noyce, 2005; Oh et al., 2010). There are limited studies that focus on exploring the relationship between accident frequency and pavement condition such as roughness and rutting. These studies showed that increasing road roughness, in general, increases the rate of accidents. Very limited information is available to determine the pavement condition level the agency needs to maintain in order to actively reduce accident risk. Transportation agencies have been looking for the appropriate roughness and rut depth thresholds before which the ride quality should be improved for safety. Decision makers need to know the cost-effectiveness of maintenance in reducing the rate of accidents, especially in accident prone areas. Research is badly needed to develop models to predict accident rates as related to pavement condition so that transportation agencies can develop appropriate pavement management strategies that reduce the frequency of pavement-related accidents.

1.2 Objectives

The main objective of this study is to investigate the relationship between accident rate and pavement condition. The study focuses on ride quality and rutting as the two main distress types that could affect accidents. General models that relate accident rates to pavement condition are developed. Accident data and pavement conditions from three states in different geographic locations and climatic conditions are collected. Accident severity levels are separated in order to investigate which accident severity is largely affected by pavement condition. Data are collected from interstate, U.S. and state roads since data on accident rates and pavement conditions are readily available. Both flexible and rigid pavements are studied without distinction. Roughness and rut depth threshold values above which crash rate largely increases are determined. If roughness and rut depth are kept below these critical values, the crash rate would largely decrease.

2.0 LITERATURE REVIEW

This section provides a brief summary of the existing research work on analyzing the effect of pavement condition on accident rate. Several pavement distresses affect accident rates such as loss of friction, roughness, and rutting. Numerous studies have investigated the effect of loss of friction between pavement and tires on accident rate (Blackburn, 1978; Hall, 2009; Kuttesch, 2004; Noyce, 2005; Oh et al., 2010). Most of the studies showed good correlations between pavement friction and crash rate since loss of friction may cause skidding when the pavement is wet. For example, Kuttesch (2004) evaluated the effect of friction factor with motor vehicle crashes in the state of Virginia and reported that there is a good correlation between the two factors. Noyce et al. (2005) found that the decrease in skid resistance lead to an increase in the wet crash rate. It was also reported that the trend could be linear or nonlinear. Similarly, Hall et al. (2009) reported the results of various studies which show that low friction factor lead to an increased crash occurrences. It was also reported that the maximum number of crashes occur with friction factor less than 0.15. However, limited studies have investigated the effect of pavement roughness and rutting on accidents. This section highlights pavement roughness and rutting and how they are interrelated to crash rate.

2.1 Pavement Roughness

Pavement roughness can be defined as irregularities in the pavement surface that adversely affect the ride equality of a vehicle (Ksaibati and Al-Mahmood, 2002). In other words, it can be defined as the deviations of a surface from a true planer surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads, and drainage (Sayers, 1985). Road roughness is considered a very important factor in analyzing the highway condition as it directly affects ride quality and other factors like vehicle delay cost, fuel consumption, etc. Due to its importance, highway agencies tend to measure and monitor road roughness on a regular basis.

2.2 Ride Quality Measurement

Pavement ride quality can either be measured subjectively or objectively. In the subjective method of measurement, the user is asked to rate his/her ride quality on a certain scale. An example of a subjective ride quality measure is the Present Serviceably Index (PSI) that was used at the AASHO Road Teat in the late 1950s and early 1960s. In the objective measurement method, the ride quality is indicated in terms of a cumulative measure of vertical displacements as recorded by a recording wheel due to the unevenness in the longitudinal profile of the road (Rao, 2017). The International Roughness Index (IRI), as developed by the world bank, is one of the most common methods used to measure ride quality and is reported in units of inches/mile or m/km. It is used to estimate ride quality in a measured longitudinal profile (HPMS Field manual, 2014). The IRI is measured using a quarter car simulation as shown in Figure 2.1 (Sayers, 1985).

The primary advantages of the IRI are:

1. It is a time-stable, reproducible mathematical processing of the unknown profile.

2. It is broadly representative of the effects of roughness on vehicle response and user's perception over the range of wavelengths of interest, and is thus relevant to the definition of roughness.
3. It is a zero-origin scale consistent with the roughness definition.
4. It is compatible with profile measuring equipment available in the U.S. market.
5. It is independent of section length and amenable to simple averaging.
6. It is consistent with established international standards and able to be related to other roughness measurements (HPMS Field manual, 2014).

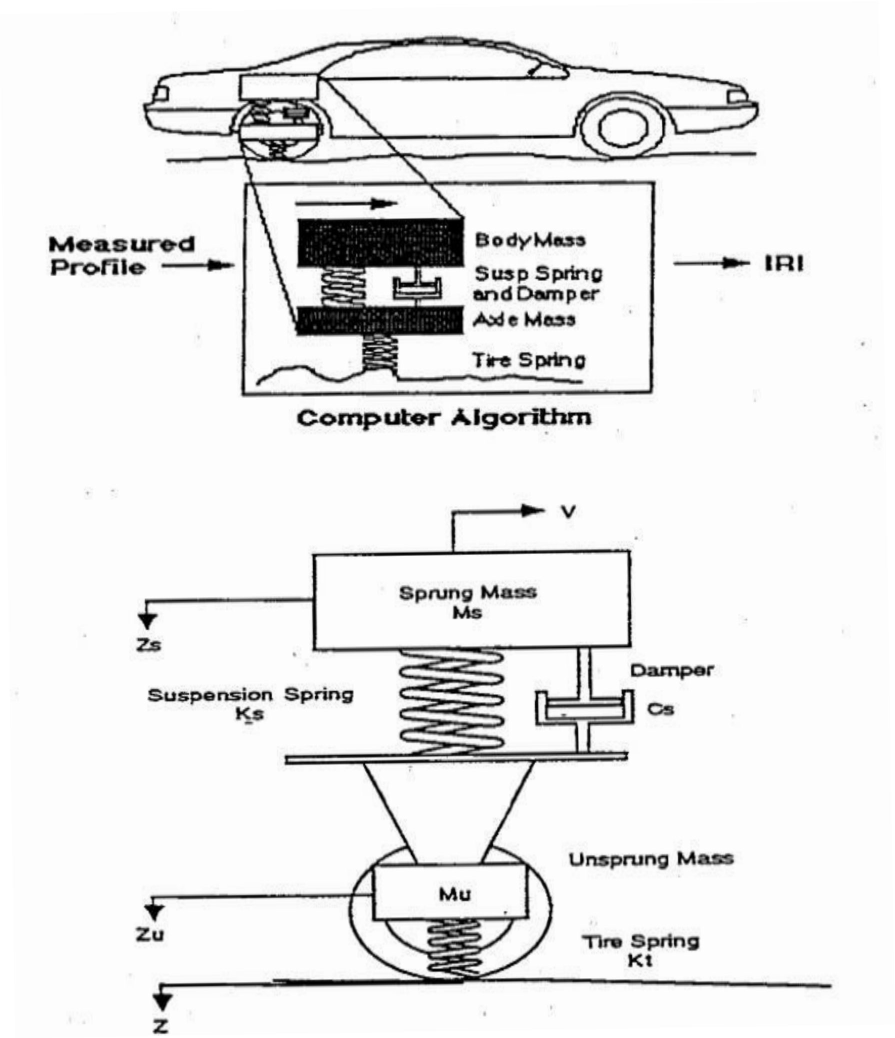


Figure 2.1. Quarter car model used to measure roughness (Sayers, 1985)

Note that IRI does not measure roughness per se, since roughness is defined as irregularities in pavement surface that is related to the micro/macro surface texture. IRI, therefore, measures the response to pavement roughness or technically "ride quality."

IRI is computed from the surface elevation data collected by either a topographic survey or a mechanical profile meter (Elghriany, 2015). It depends on the average rectified slope (ARS), which is used as a filtered ratio of a standard vehicle's accumulated suspension motion divided by the distance traveled by the vehicle during the measurement period. As a result, IRI equals ARS times 1,000 (WSDOT, 2009).

Figure 2.2 shows the open-ended IRI scale with typical IRI values that correspond to different pavement conditions for different pavement types.

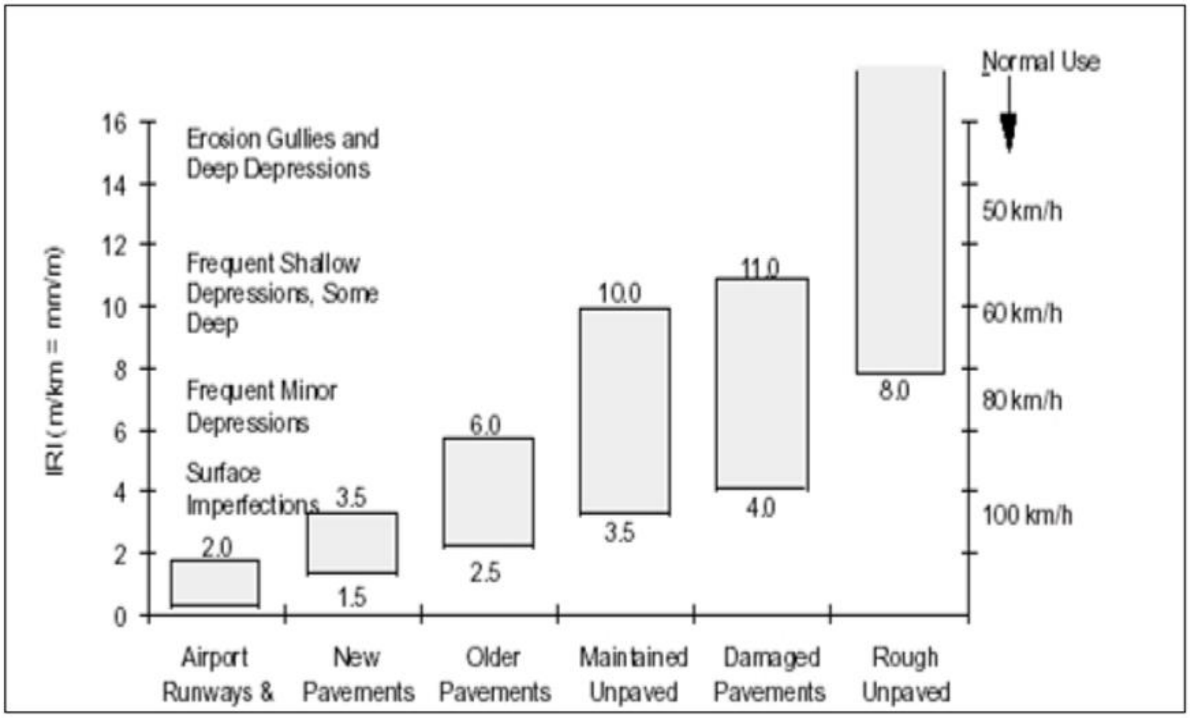


Figure 2.2. IRI ride quality scale (Sayers et. al, 1985)

Pavement roughness affects not only ride quality, but also vehicle life, fuel consumption of vehicle, and delay cost. More importantly, pavement roughness can cause vehicle's loss of control when braking or turning (Chan et. al, 2008 and Bester, 2003). Traction between tire and pavement is essential for vehicle steering and braking. Braking mechanism uses the friction between tire and pavement to stop the vehicle. When the pavement roughness increases, the contact area between vehicle tire and pavement decreases, thus leading to a lower brake friction (Wambold, 1973 and Nakatsuji, 1990). Furthermore, it may be difficult to control vehicles when the drivers rotate the steering wheel because rough pavement reduces the normal force and also the lateral force (Wambold, 1973). Pavement roughness can also contribute to vehicle skidding on pavement because the traction forces may be different for the tires on either side of the vehicle. Also, vehicles bouncing up and down on extremely rough pavements may result in vehicle losing their loads causing accidents (Burns, 1981).

In a study conducted by Chandra et al. (2013), it was reported that pavement distresses like potholes, total cracked area, and raveling had a significant impact on pavement roughness. It was also reported that rut depth and patching have severe impact on road roughness.

In another study, Zhou and Wang (2008) reported that the distress characteristics directly influence the IRI value. Lin and Hsiao (2003) studied the relation between IRI and distress factors and found a correlation factor (R^2) of 0.944. The results from these researches indicate that IRI and pavement distresses go hand in hand and IRI can be used as a measure of pavement distresses.

2.3 Pavement Rutting

Rutting is defined as a longitudinal depression in the wheel path(s) of a paved surface measured between the width limits of the lane (HPMS Field Manual, 2014). It may be the result of deformation of the pavement surface, base, subbase or subgrade (Huang, 2004, Cenek et al, 2014). Rutting data are collected and reported in inches or millimeters.

Rutting is caused when the traffic load displaces the material and causes depression. The material can be displaced laterally from the wheel path or towards the shoulder and centerline and between the wheel tracks, or vertically (MDOT Research Record, 1996).

In dry conditions, rutting will act as a wheel path; but the driver may need extra effort to get out from the rut path if the rut depth is large. Rutting is more hazardous in wet weather when water accumulates in the rut path and leads to hydroplaning as shown in Figure 2.3. Hydroplaning is defined as a condition wherein vehicles' tire separated from the pavement due to the pressure of the fluid underneath the tire (Strat et. al, 1998). Hydroplaning had been categorized into three categories: viscous hydroplaning, dynamic hydroplaning, and tire-tread rubber-reversion hydroplaning (TRC E-C 134, 2009). Viscous hydroplaning may occur at any speed with extremely thin film of water and little micro-texture on the pavement surface. Dynamic hydroplaning occurs when vehicles travel at high speeds, resulting in insufficient time for removing water underneath the tire. Tire-tread rubber-reversion hydroplaning occurs only when heavy vehicles lock the wheels while moving at high speed on wet pavement. Strat et al. (1998) suggested that 0.3 in. rut depth is the point at which significant increase in accident frequency occurs.

Figure 2.3. Example of pavement rutting with water accumulation (Miller and Bellinger 2003)

2.4 Motor Vehicle Accidents/Crashes

Motor vehicle accidents are one of the major challenges that faces transportation engineers and researchers. Road accidents have a huge economic and social impact on the society. According to the Bureau of Transportation Statistics, the estimated total cost of motor vehicle crashes in the U.S. was about $836 billion in 2010. The broader accident societal costs, including lost quality of life, account for 71 percent of the total, far outweighing the economic costs at 29 percent. Also, the highway motor vehicle fatalities rose 7.2 percent in 2015 as the 35,092 highway deaths alone exceeded the 2014 number for all transportation fatalities (34,641). The number of people injured in highway motor vehicle accidents increased by an estimated 105,000 to 2.44 million in 2015 – the first increase in the highway injury count since 2012. Hence it is important to understand the causes and the fluctuations in the crashes to reduce the number of crashes.

2.5 Relation between Pavement Condition and Safety

As stated earlier, accident rate is affected by several factors such as human factors, vehicular causes, environment, roadway geometry, traffic volume, pavement condition, and their combinations. Studies show that the majority of accidents are caused by human factors such as distraction, alcohol, stress, physical deficiency and age. Pavement condition, however, causes a small percentage of accidents as compared to human factors (Garber, 2015). In spite of its small influence on accidents, maintaining good pavements would likely reduce the accident rate.

King (2014) investigated the effect of road roughness on traffic speed and road safety in Southern Queensland, Australia. The study found a strong relationship between higher crash rates and increased pavement roughness. Crash rates involving light vehicles were more affected by increasing roughness than crashes involving heavy freight vehicles. Considering different crash severity levels, crashes resulting in hospitalizations and property damage had the strongest increase in crashes over a small increase in roughness. The study also found that speed is reduced when roughness increases. The study recommended that traffic authorities managing rural roads need to reduce roughness to an IRI value of 120 in./mile in order to provide a safer road environment. Providing incentives to contractors for delivering a smooth pavement over the design life will ensure better pavement and construction quality. Figures 2.4 and 2.5 show sample results obtained in that study.

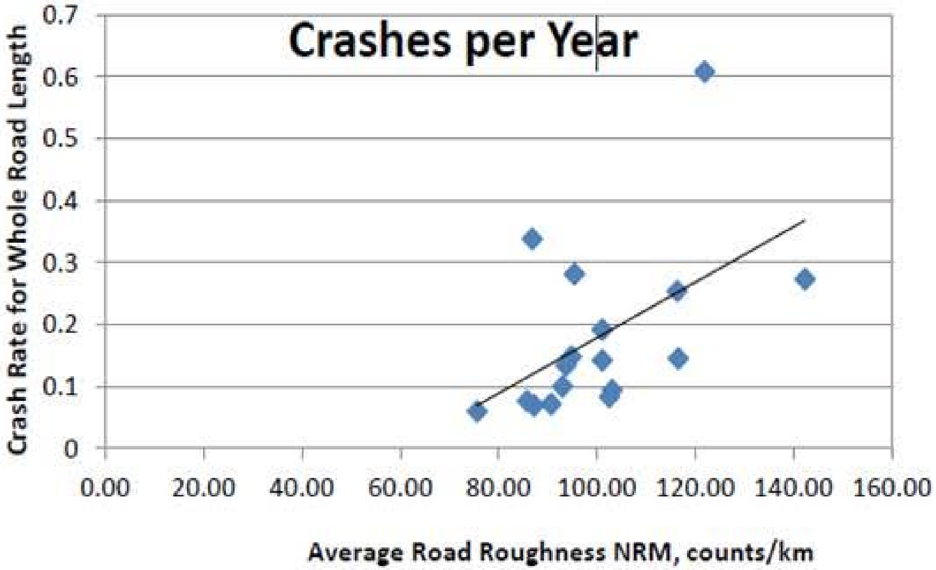


Figure 2.4. Crash rate vs. roughness plot (King, 2014)

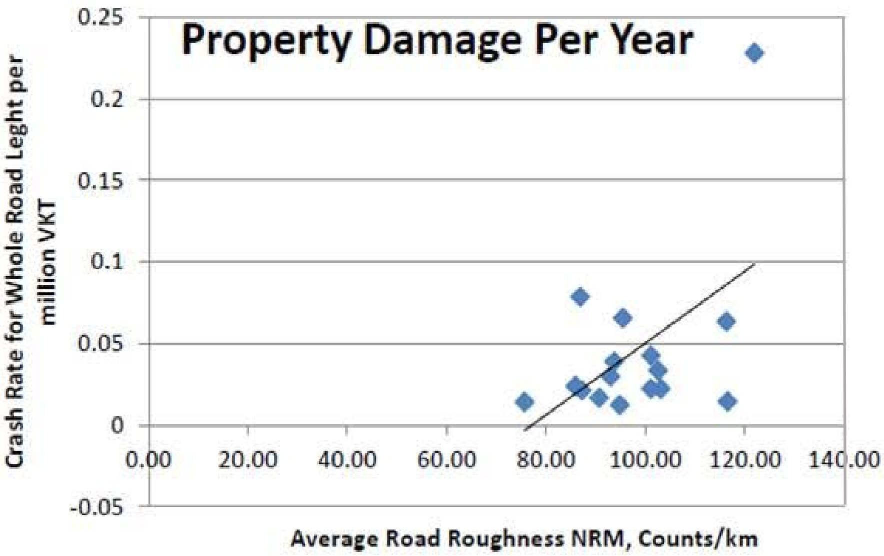


Figure 2.5. Crash Rate vs. roughness plot for property damage only crashes (King, 2014)

Chan et al. (2010) noted that very few researches investigated the effect of pavement roughness and rutting on accident rate. However, some of the other factors causing crashes have been studied extensively. Cairney and Bennet (2008) performed a study to determine the relationship between pavement surface characteristics and roadway crashes in Victoria, Australia. The authors measured the pavement properties using multi–laser profilometer and linked them to crash data with the help of the Global Positioning System (GIS). They found that there was good correlation between roughness and crash rate following a polynomial relationship. However, no clear relationship could be found between rutting and crash rate. Also, the extreme roughness which was associated with high crash rate was only over a small proportion of the road network analyzed.

In another study by Graves et al. (2005), the authors found that a disproportionate number of crashes was associated with certain pavement conditions, hence suggesting that they are correlated. The analysis was performed in Alabama and further suggested data mining could be a useful tech1nique in the analysis process.

Li et al. (2013) performed a study using crash and pavement data from the Texas Department of Transportation (TxDOT) database between the years 2008 and 2009. The study examined the relationship between crash severity and factors indicating the pavement condition. Results indicated that crashes of higher severity occurred on roads with poor pavement condition compared to the roads with fair pavement condition. It was also noted that relatively higher severity crashes occurred on roads with very good pavement condition. Purposefully laying down rougher pavements on high speed roadways was suggested as a potential solution to avoid high severity crashes.

However, a more recent study by Li (2014) indicated that pavement with poor surface conditions are responsible for higher crash rates. The author also stated that the research work available in determining the relationship between crashes and pavement condition is limited.

Tehrani et al. (2012) explored the relationship between the IRI value and number of collisions in the province of Alberta, Canada. Three major highways with high crash rates and different values of IRI were selected in the study and the results indicated that the sections with high IRI values have more crashes in comparison to those with low IRI values. Also, the results indicated that there was a good correlation between rut depth and number of crash in 1 kilometer segments. On the contrary, a study performed by Cenek and Davis (2004) showed that there is no significant correlation between IRI and safety.

Cenek et al (2014) performed another study to develop statistical models predicting the correlation between rut depths and fatal and injury crashes on New Zealand's State highway network. The results indicated that there was an increase in crash rate where the rut depth is 10 mm or higher. The study suggested that these accidents might have been caused by the accumulation of water on the road surface. The authors concluded that the crash rate, for dry crashes in particular has decreased slightly in sections where the rut depth is slightly higher than the normal range.

Chan et al. (2010) performed a study to understand the relationship between accident frequency and pavement condition using IRI, rut depth and PSI as parameters for pavement condition. The study used Accident History Database (AHD) and Tennessee pavement management systems data focusing on four urban interstates with asphalt pavement and a speed limit of 55 mph. The results show that IRI and PSI were significant in all types of models, whereas the rut depth model performed well in predicting the accidents that occurred during night time only.

Hu et al. (2013, 2017) developed mathematical relationships between IRI and driving comfort and safety (driving workload). The authors developed threshold IRI values on road segments at different risk levels for driving comfort and safety. They also concluded that standard IRI values for pavement maintenance are beyond the comfort and safety threshold for both car and truck drivers.

In conclusion, it can be suggested that pavement condition can be considered a contributing factor for traffic safety and crash occurrence. The literature suggests that while evaluation of pavement roughness, more specifically IRI, has good correlation with crash rate and effects the crash severity, the contribution of rut depth to traffic safety is not well defined. No guidelines are currently available in the literature to assist highway maintenance authorities to maintain their pavement conditions at a certain level in order to minimize crash occurrences.

3.0 DATA COLLECTION, PROCESSING AND ANALYSIS

3.1 Background

This study analyzes crashes that occurred on interstate, state and U.S. highways in the states of Arizona, North Carolina and Maryland between 2013 and 2015.

The types of data required for the analysis were as follows:

1. Crash data
    a. Crash location
    b. Crash severity
2. Pavement condition data
    a. Roughness data
    b. Rutting data
3. Traffic data
    a. Average Annual Daily Traffic (AADT)

These data are typically available in different databases/websites and it varied from one state to another. Data were collected from public domain depending on the availability. In other cases, state Departments of Transportation (DOTs) were contacted and data were requested. Several of the contacted states did not respond or indicated that accident data cannot be sent to the public. In fact, accident data were hard to obtain, which limited the study to three states. Also, one of the difficulties in collecting and processing the data was the lack of uniformity of reporting the data between different states.

Though various other factors like geometric design, driver condition, weather, etc., could be responsible for the crash occurrence, this study focuses only on pavement surface condition, excluding friction.

3.2 Data Sources and Collection

Since PMS and accident data are typically reported in different databases for each state, the different data sets had to be matched. In the study, the pavement surface condition is matched with the roadway crashes. Hence several data sources were used with location information as the criteria to match the data. This section highlights the data collection process for each of the states.

3.2.1 Arizona

3.2.1.1 Crash Data

The crash data for the years of 2014 and 2013 were collected from Arizona Department of transportation (ADOT). The following information from the crash data was used for the research.

a. Road name

Interstates, state and U.S. highways were considered for the analysis.

b. Milepost

   The milepost was rounded off to the nearest whole number hence conducting the analysis for 1 mile segments.

c. Travel direction

d. Accident severity

   Accident severity was classified into 5 categories, 1 being property damage and 5 being a fatal crash.

3.2.1.2 Pavement Management Systems Data

The pavement management system data was obtained from the Arizona Department of transportation (ADOT). The following road data were used for this research.

a. Milepost
b. Direction
c. Average IRI
d. Average Rut depth

Traffic data (AADT) was also collected from the state DOT and was matched with the crash and PMS data for the final analysis. It can be noted that analysis for rutting was not completely performed for the year 2013. This was due to the fact that there was a problem with the profiler and hence rutting was collected only on a small portion of the highway network which was not sufficient to perform the analysis.

3.2.2 North Carolina

The crash and pavement management systems data and AADT for North Carolina were obtained from North Carolina Department of Transportation (NCDOT) for the year of 2015.

3.2.2.1 Crash Data

The crashes caused due to snow were filtered out and was not considered for the analysis. The data that were collected were:

a. Route ID
b. Travel direction
c. Milepost
d. Accident severity

Accident severity was classified into 5 categories, i.e., 1 (Property damage only), C (Possible Injury), B. Injury (Evident), A. Injury (Disabling) and 5 (Fatal Injury).

3.2.2.2 Pavement Management Systems Data

a. Route ID

b. Effective year
c. Measurement direction
d. Average rut depth
e. Average IRI
f. Milepost

3.2.3 Maryland

3.2.3.1 Crash Data

Crash data for Maryland were obtained from the Maryland government open data portal, which includes accidents that occurred on Maryland Transportation Authority (MDTA), which were reported by the Maryland police for the year of 2014.

The following information was used for the analysis.

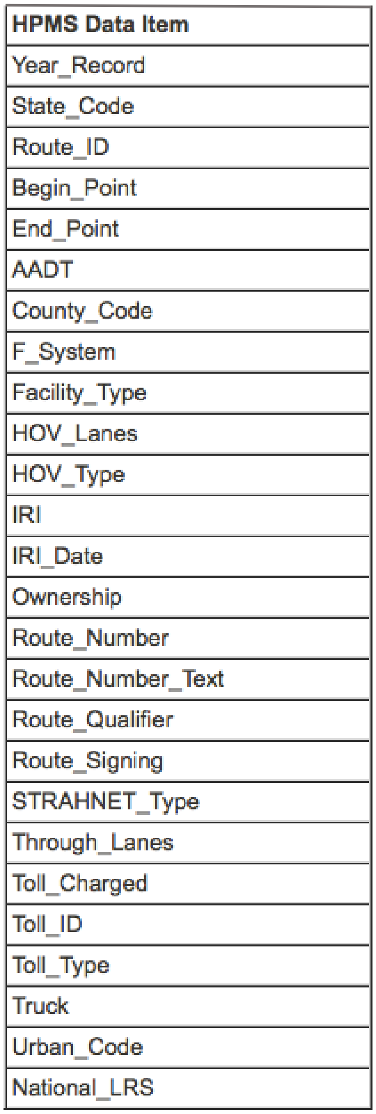
a. Latitude
b. Longitude
c. Crash severity

The crash severity was divided into three categories, namely Property Damage, Injury Occurrence and Fatal Crashes. Essentially, the severities 2, 3 and 4 of Arizona and A, B, and C of North Carolina are equivalent to Injury Occurrence classification of Maryland.

3.2.3.2 Pavement Management Systems Data

The PMS data were obtained from two different sources. The IRI data were obtained from the Highway Performance Monitoring System (HPMS) public release of open source data, which also contains the AADT data. The data are geocoded and are available in the shape file format. The data are collected for highways that are a part of HPMS defined federal aid system. The data are available from the year 2012 to 2015 for all the states in the U.S.

Figure 3.1 shows the field manual detailing the data that are available in the HPMS geospatial data. The data are collected from different state DOTs and are geocoded and compiled. While certain attributes of the highway are collected for all the road sections for all segments or full extent, certain other attributes are collected only for sample sections. IRI and AADT data are recorded for all the road segments, while rut depth data are available only for the sample panel.



HPMS Data Item
Year_Record
State_Code
Route_ID
Begin_Point
End_Point
AADT
County_Code
F_System
Facility_Type
HOV_Lanes
HOV_Type
IRI
IRI_Date
Ownership
Route_Number
Route_Number_Text
Route_Qualifier
Route_Signing
STRAHNET_Type
Through_Lanes
Toll_Charged
Toll_ID
Toll_Type
Truck
Urban_Code
National_LRS

Figure 3.1. HPMS data attributes list

The rut depth was obtained from the Maryland State Highway Administration (Maryland SHA). The following information was used from the data.

a. Begin latitude

b. Begin longitude

c. End latitude

d. End longitude

e. AADT

f. Average rut depth

g. Average IRI

f. Road name

g. Milepost

Table 3.1 shows the devices used to measure ride quality and rutting data in the three states. Arizona uses the same piece of equipment to measure both ride quality and rutting, while other states use different pieces of equipment (Figure 3.2). Table 3.1 shows that different states may use either the same or different equipment type to measure a specific distress type. These differences could be because of the actual differences in pavement conditions or because of other reasons. Mamlouk and Zapata (2010) showed that there are several reasons that would make the PMS data different for different agencies. Reasons for these differences include types of data measured, types of measuring equipment, data processing methods, units of measurements, sampling methods, unit length of pavement section, and number of runs of measuring devices.

Table 3.1. Devices used to measure ride quality and rutting data in the three states

State	Ride quality measuring device	Rutting measuring device
Arizona	Profilometer	Profilometer
North Carolina	Profiler	Profilometer
Maryland	Automatic Road Analyzer (ARAN)	ARAN

Figure 3.2. Profilometer used by the Arizona Department of Transportation to measure both ride quality and rutting

Previous discussion shows that accident data were reported at 5 levels of severity. Although the severity levels are similar in different states, they are named differently. Table 3.2 summarizes the severity levels used in the three states.

Table 3.2. Severity levels in different states

Severity Level	Arizona	North Carolina	Maryland
1	Damage without injury	Damage without injury	Property damage
2	Minor injury	Injury level C	Physical injury
3	Non-incapacitating injury	Injury level B	
4	Incapacitating injury	Injury level A	
5	Fatality	Fatality	Fatality

3.3 Data Processing

After obtaining the raw data from various sources that were discussed in the section above, data processing was performed. Data processing involved cleaning the raw data and performing initial screening in order to make the data useful for performing further statistical analyses. As the data were collected from various sources, compiling the data and bringing all the available data into the same format was tedious and time consuming. For instance, the location column and determining the crash occurrence were provided in two different formats in crash data and PMS data. It was necessary to make sure they are presented in the same format before proceeding with further analysis.

3.4 Data Analysis

3.4.1 Crash Data Analysis

Crash events are rare occurrences. Crash data can help understand the cause of crashes, identify crash prone area locations, understand where high severity crash occurs and aid in the choice of safety programs (Robertson 1994). Crash analysis is performed in order to improve safety and identify the factors that are responsible for crash occurrence.

3.4.1.1 Crash Frequency

Crash frequency is the number of crashes that occur at a particular location over a given period of time. Crash frequency can be obtained from the data source by summing up the total number of crashes that occur at a particular location. The analysis period for the study was selected to be one year and hence the total number of crashes occurring in a year is summed up to obtain crash frequency.

3.4.1.2 Crash Rate

While crash frequency is a useful tool to compare the variation of number of crashes occurring at a given location and helps in observing trends, it is often inadequate to compare the crash occurrences for multiple locations. This is simply because the crash frequency analysis does not consider traffic factors or length of the road segments on which the crashes occur.

For example, consider two locations A and B. Assuming the number of motor vehicle crashes that occur at both the locations are equal, if the number of vehicles passing through location A is higher than that of location B, the two locations cannot come under the same priority level. In such cases, crash data need to be normalized to obtain a crash rate that can be used to provide better judgments and help prioritizing locations for safety analysis.

A widely-accepted approach to calculate crash rate is using the U.S. Department of Transportation method, which can be calculated using the formula mentioned below.

As crash occurrences are not that frequent, the formula calculates the crash rate per 100 million vehicles.

$$CR = \frac{C \times 100{,}000{,}000}{V \times 365 \times L \times N} \tag{3.1}$$

where,

CR = Average number of crashes in each category in the study period

V = Average traffic volume entering the study area daily or Average annual daily traffic (AADT)

L = Length of the road segment used for analysis

N = Number of years of data

In this study, crash rate has been calculated, taking 1-mile road segments into consideration. Analysis has been done for each year and hence, the value of N = 1 throughout the analysis.

3.4.2 Pavement Data Analysis

Pavement data include average IRI and average rut depth at each mile. While the units of measurement for IRI and rut depth are the same for all states, the length of the segment the data was provided for varied from one state to another. Details on data analysis for each of the states are discussed in this section

3.4.2.1 Arizona

For the state of Arizona, pavement management systems (PMS) data were provided for each mile post and were directly used for analysis without making any changes.

3.4.2.2 North Carolina

For the state of North Carolina, the PMS data were provided for every 0.1 miles. In order to maintain uniformity throughout the analysis, the PMS data was averaged to every mile. Average IRI, average rut depth and average AADT were calculated for each milepost and the modified data were used in the analysis. In this way, it was made sure that the length of segments used for analysis is consistent with other states.

3.4.2.3 Maryland

For the state of Maryland, the rut depth data were provided for every 0.1 miles and the data was averaged for every mile, similar to the North Carolina data. The IRI data obtained from HPMS were provided for road segments that are less than 1 mile. Using the route ID and milepost data, IRI data were averaged for every mile for the sake of consistency.

3.5 Data Integration and Merging

As the duration of analysis is one year for the study, the data were sorted and separated for each year. Crash data and PMS data were matched and merged together on the basis of location. For Arizona and North Carolina, data matching was performed by taking road name and milepost as common criteria. However, for Maryland, data were matched using latitude and longitude or GIS coordinates as the matching criteria. The PMS data available in the shape file format were extracted using ArcGIS and were converted into csv files for use in further analysis. GIS coordinates along with the route ID which give information about road name and milepost were obtained from the shape files.

After obtaining the filtered data, SQL queries were used to correlate the data and obtain the necessary results. SQL queries were written for all the crashes and for each severity level separately. After matching the data using SQL, Microsoft Excel was used to perform further analysis, and grouping the data on the basis of IRI and rut depth.

3.6 Summary

This section highlights the data collection, processing and analysis that have been performed in the study. The data includes crash information, traffic (AADT), IRI and rut depth that are used in the analysis. The section also talks about the crash rate approach that was used in the study.

4.0 ANAYSIS OF RESULTS

Data analysis was performed to study the relationship between crash rate and both IRI and rut depth. This section presents the regression models and the results of the analysis performed in the study. It presents with the graphs that show the relationship between the crash rate and either IRI or rut depth for all crashes put together and for each of the injury severities separately.

4.1 Statistics

4.1.1 Pavement Management Systems Data

Table 4.1 presents with the basic statistics of the pavement management systems data of the data obtained from the three states. The tables highlight the average, value, standard deviation, and minimum and maximum values for IRI and rut depth. It can be noticed from the table that there are variations in IRI and rut depth values between the states.

4.1.2 Crash Data Summary

Table 4.2 presents the crash frequency data used for the analysis. The data are divided into different severity levels as discussed in Section 3. The crashes for North Carolina exclude crashes caused due to snow. It can be noticed that the number of crashes used for analysis for the state of Maryland is considerably lower than the other states. This is due to the fact that data obtained did not cover the whole state. Open source data were available only for the crashes that occurred in the MDTA facilities and were reported to the police. Therefore, the crash rates used in this study do not represent the actual crash rates of the state of Maryland. Note also that severity levels 2-4 (physical injury) are combined in the state of Maryland. Also, no fatality crashed were reported in this Maryland sample of data.

Table 4.1: Summary statistics of IRI and rutting data

State (Year)	Variable	Mean	Standard Deviation	Minimum	Minimum
Arizona (2013)	IRI (in./mile)	72.2	31.2	0	248
Arizona (2014)	IRI (in./mile)	71.64	32.9	0.06	421.3
	Rut Depth (in.)	0.055	0.046	0	0.44
North Carolina (2015)	IRI (in./mile)	101.5	42.9	29.9	449.5
	Rut Depth (in.)	0.140	0.063	0	0.482
Maryland (2014)	IRI (in./mile)	132.8	86.56	33	459
	Rut Depth (in.)	0.15	0.051	0	0.39

Table 4.2: Summary statistics of total crash data

State (Year)	All Severities	Severity Level 1	Severity Level 2	Severity Level 3	Severity Level 4	Severity Level 5
Arizona (2013)	31,514	21,748	4,473	4,149	838	306
Arizona (2014)	32,570	22,809	4,454	4,296	767	243
North Carolina (2015)	97,612	67,601	20,625	6,702	835	601
Maryland* (2014)	807	607	204			-

*Partial data were obtained

4.1.3 Crash vs. Non-Crash Segments

The highways studied in the analysis can be divided into crash and non-crash segments. Crash segments are the road networks on which at least one accident has occurred in the study period of one year. On the other hand, non-crash segments can be defined as the part of the study area on which no crashes have happened during the study area. One measure of the effect of roughness and rutting on the number of accident is to compare the average roughness and rutting values of non-crash with those of crash segments. A larger roughness and/or rutting average of crash segments than those of non-crash segments would prove a negative effect on safety. Table 4.3 shows percent of length of crash segments relative to length of the whole pavement network in the different states-years. The table also shows the average IRI and rut depth of crash and non-crash segments. Note that crash and non-crash data are not available for Maryland since crash data for Maryland are available as GIS coordinates and also the analysis was not performed on all the roads. Therefore, crash and non-crash segments could not be separated in Maryland.

Table 4.3: Crash and non-crash segments

State (Year)	Percent Length of Crash Segment	IRI (in./mile)		Rut Depth (in.)	
		Non-Crash Segments	Crash Segments	Non-Crash Segments	Crash Segments
Arizona (2013)	36.6%	86.37	72.2	-	-
Arizona (2014)	40.6 %	84.87	71.64	0.060	0.055
North Carolina (2015)	47.8%	123.6	102.77	0.134	0.140

The table shows that the length crash segments represent 37-48 percent of the total length of the network in different states using 1-mile segments. The table also shows that ride quality and rutting values of crash and non-crash segments in each state-year are close to each other. This suggests that ride quality and rutting are not the only factors affecting number of crashes but possibly in combination with other factors such as traffic volume, human factors, etc.

Another measure of the effect of ride quality and rutting on the number of accident is to evaluate the relationship between crash rates and both ride quality and rutting measurements for different accident severity levels. Since accidents are relatively rare, crash segments only were used in this part of the analysis. If both crash and non-crash segments are used, the large number of non-crash segments will dominate the analysis and skew the results.

4.2 Ride Quality Analysis

For each state and each crash severity level, the IRI values were broken down to categories of 50. For each category, the number of miles, average crash count, and average AADT were compiled and the corresponding crash rate was calculated according to Equation 3.1.

Several curve fitting functions were tried such as exponential, power, etc. The sigmoidal function provided the best fit among other functions. Sigmoidal function models were developed between the average crash rates and either the average IRI value or the average rut depth value for each category. During the analysis, data points that are obviously outside the typical range were removed from the analysis. Equation 4.1 shows the sigmoidal function used in each category.

$$\log CR = \delta + \frac{\alpha}{1+e^{\beta+\gamma(log f_r)}} \tag{4.1}$$

where:

CR = Crash rate per 100 million vehicle miles travelled per year
f_r = Average IRI (in./mile)
δ = minimum logarithmic value of CR
$\delta+\alpha$ = maximum logarithmic value of CR
β, γ = parameters describing the shape of the sigmoidal function

4.2.1 Arizona 2013

Figure 4.1 shows the relationship between crash rate and IRI values for all severity levels combined, while Figure 4.2 shows similar relationships for severity levels 1-5. All graphs show that crash rate does not basically increase up to a certain IRI value, above which crash rate starts to increase. This phenomenon suggests that if the IRI value is kept below a certain value, crash rate can be reduced.

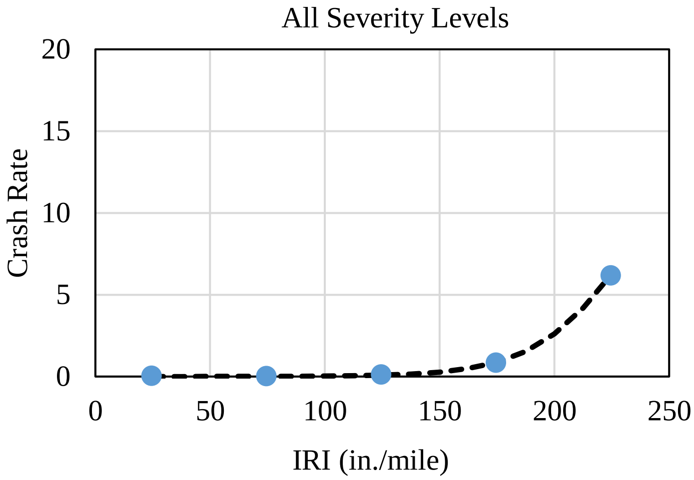


Figure 4.1. Relationship between crash rate and IRI values for all severity levels combined (Arizona 2013)

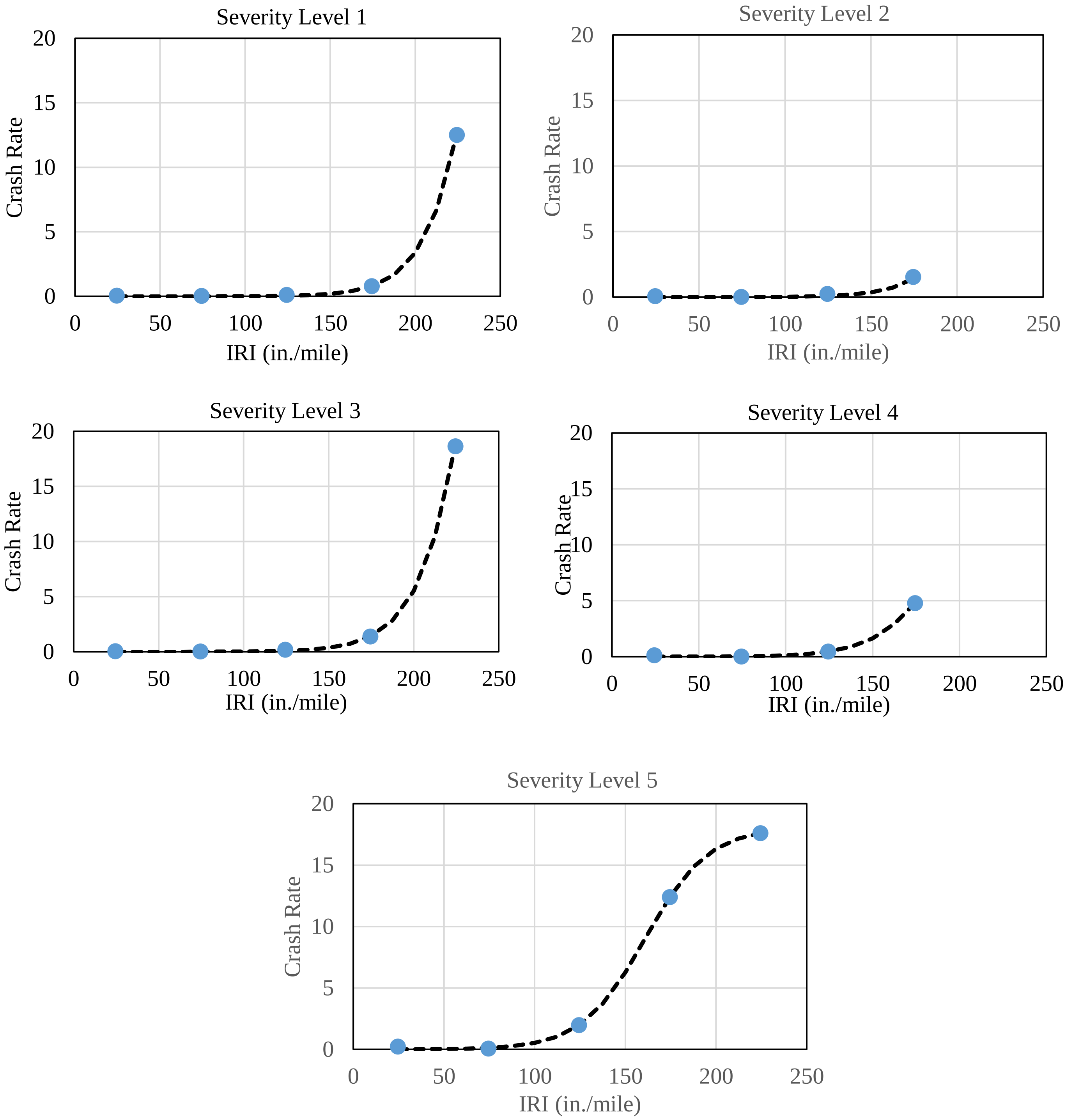


Figure 4.2. Relationship between crash rate and IRI values for severity levels 1-5
(Arizona 2013)

4.2.2 Arizona 2014

Figure 4.3 shows the relationship between crash rate and IRI values for all severity levels combined, while Figure 4.4 shows similar relationships for severity levels 1-5. All graphs show that crash rate does not mainly increase up to a certain IRI value, above which crash rate starts to increase. This phenomenon suggests that if the IRI value is kept below a certain value, crash rate can be minimized.

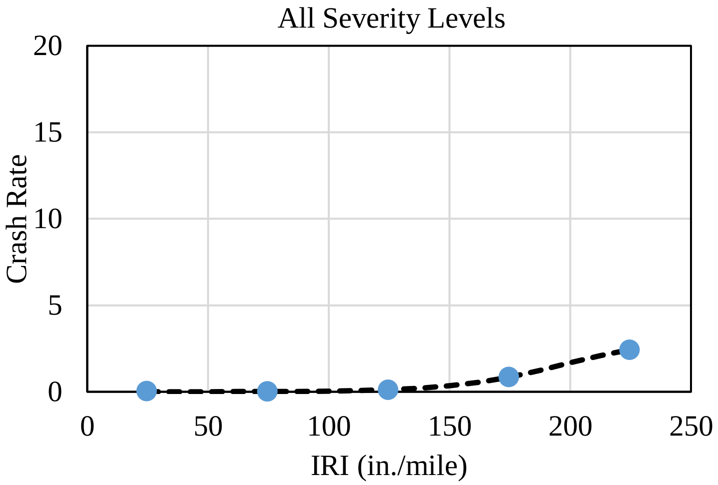


Figure 4.3. Relationship between crash rate and IRI values for all severity levels combined (Arizona 2014)

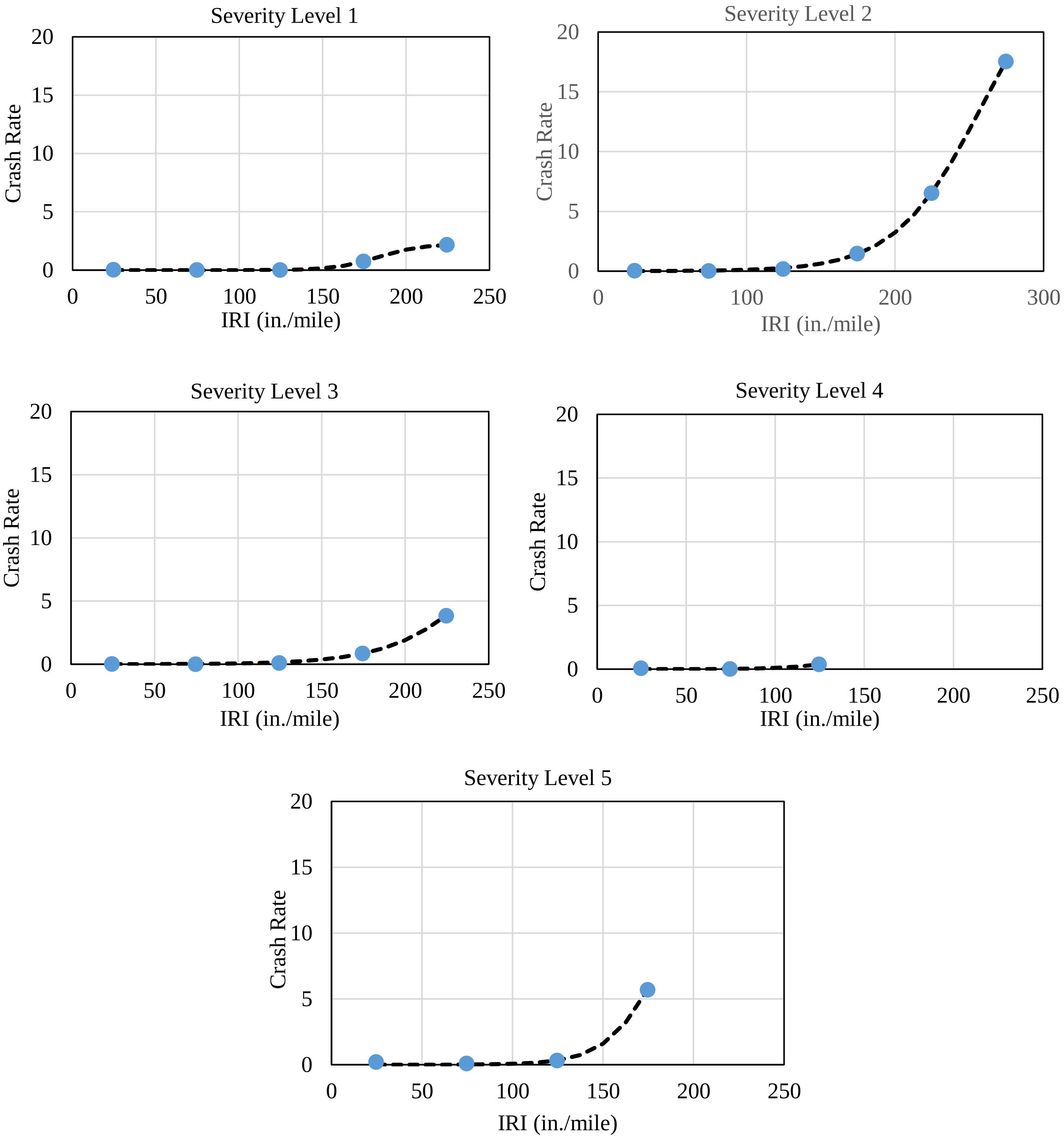


Figure 4.4. Relationship between crash rate and IRI values for severity levels 1-5 (Arizona 2014)

4.2.3 North Carolina 2015

Figure 4.5 shows the relationship between crash rate and IRI values for all severity levels combined, while Figure 4.6 shows similar relationships for severity levels 1-5. Similar to the Arizona results, all graphs show that crash rate does not generally increase up to a certain IRI value, above which crash rate begins to increase. This phenomenon suggests that if the IRI value is kept below a certain value, crash rate can be decreased.

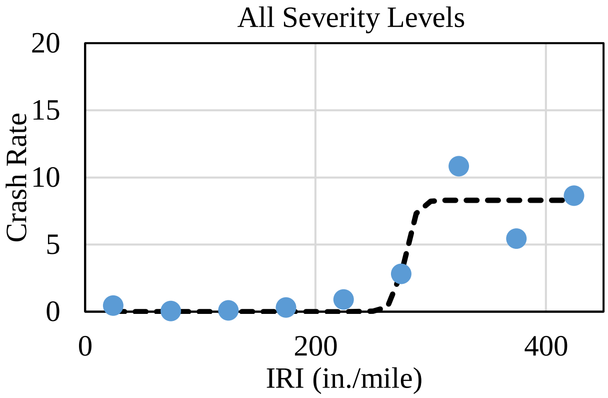


Figure 4.5. Relationship between crash rate and IRI values for all severity levels combined (North Carolina 2015)

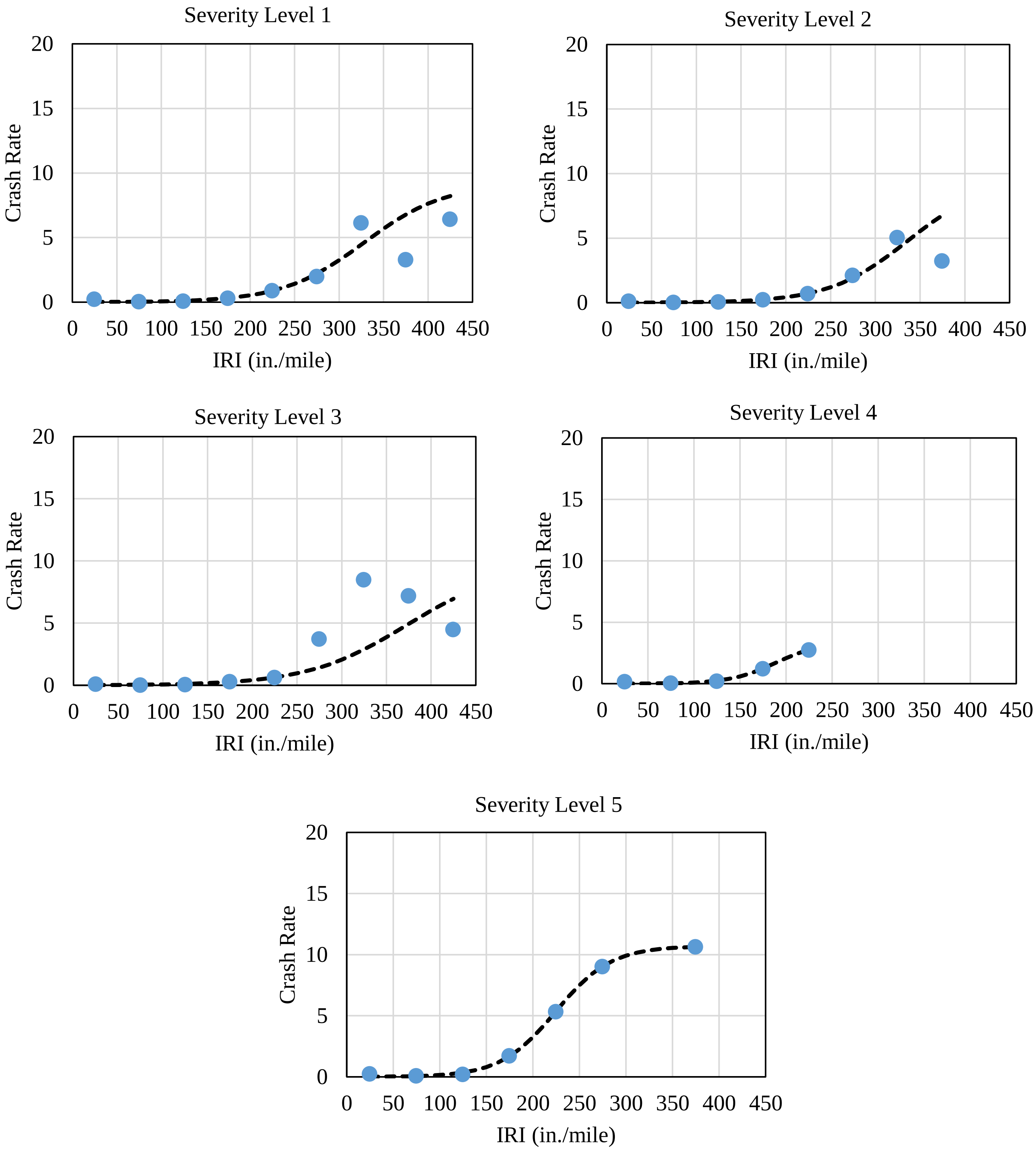


Figure 4.6. Relationship between crash rate and IRI values for severity levels 1-5 (North Carolina 2015)

4.2.4 Maryland 2014

As indicated earlier, the number of crashes used for analysis for the state of Maryland is considerably lower than the other states. This is due to the fact that data obtained do not cover the whole state since the rest of crash data are not publicly available. Therefore, the crash rates used in this study do not represent the actual crash rates of the state of Maryland. They were used in this study only to study there trend with IRI data, but not to show the actual crash rate values.

Figure 4.7 shows the relationship between crash rate and IRI values for all severity levels combined, while Figure 4.8 shows similar relationships for severity level 1 and levels 2-4 combined. As indicated earlier, no fatality crashed were reported in this sample of data in Maryland. Similar to the Arizona and North Carolina results, all graphs show that crash rate does not essentially increase up to a certain IRI value, above which crash rate starts to increase. This phenomenon suggests that if the IRI value is kept below a certain value, crash rate can be decreased.

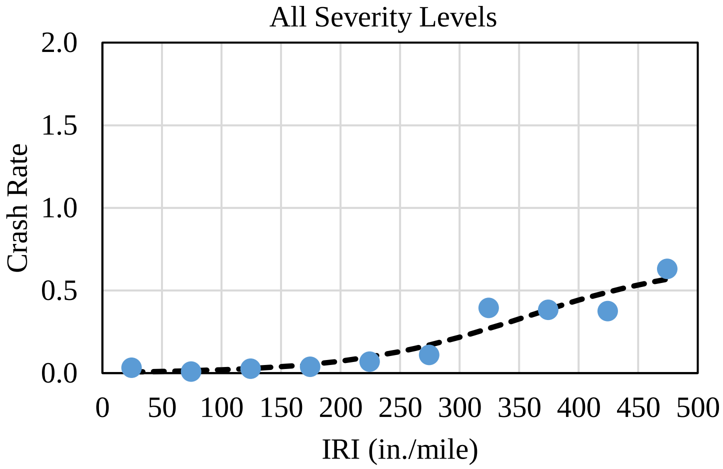


Figure 4.7. Relationship between crash rate and IRI values for all severity levels combined (Maryland 2014)

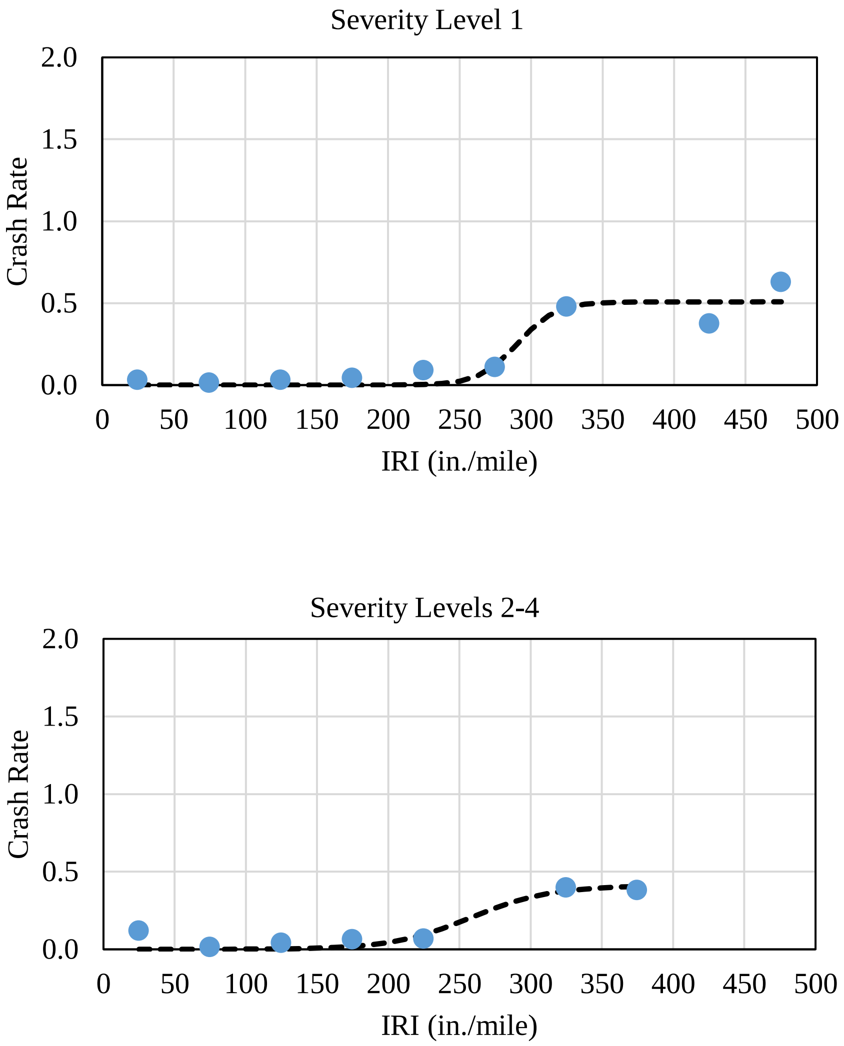


Figure 4.8. Relationship between crash rate and IRI values for severity level 1 and levels 2-4 (Maryland 2014)

4.3 Rutting Analysis

Similar to IRI data, the rut depth values were broken down to categories of 0.1 inches for each state and each crash severity level. Sigmoidal function models (similar to Equation 4.1, except that f_r is the average rut depth in inches) were developed between the average crash rates and the average rutting value for each category.

4.3.1 Arizona 2014

Figure 4.9 shows the relationship between crash rate and rut depth for all severity levels combined, while Figure 4.10 shows similar relationships for severity levels 1-5. All graphs show that crash rate does not largely increase up to a certain rut depth value, above which crash rate increase rapidly. This phenomenon suggests that if the rut depth value is kept below a certain value, crash rate can be reduced.

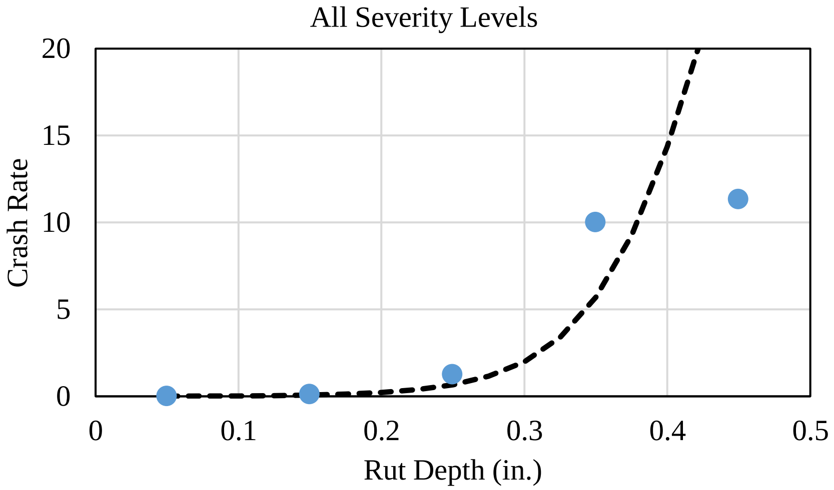


Figure 4.9. Relationship between crash rate and rut depth for all severity levels combined (Arizona 2014)

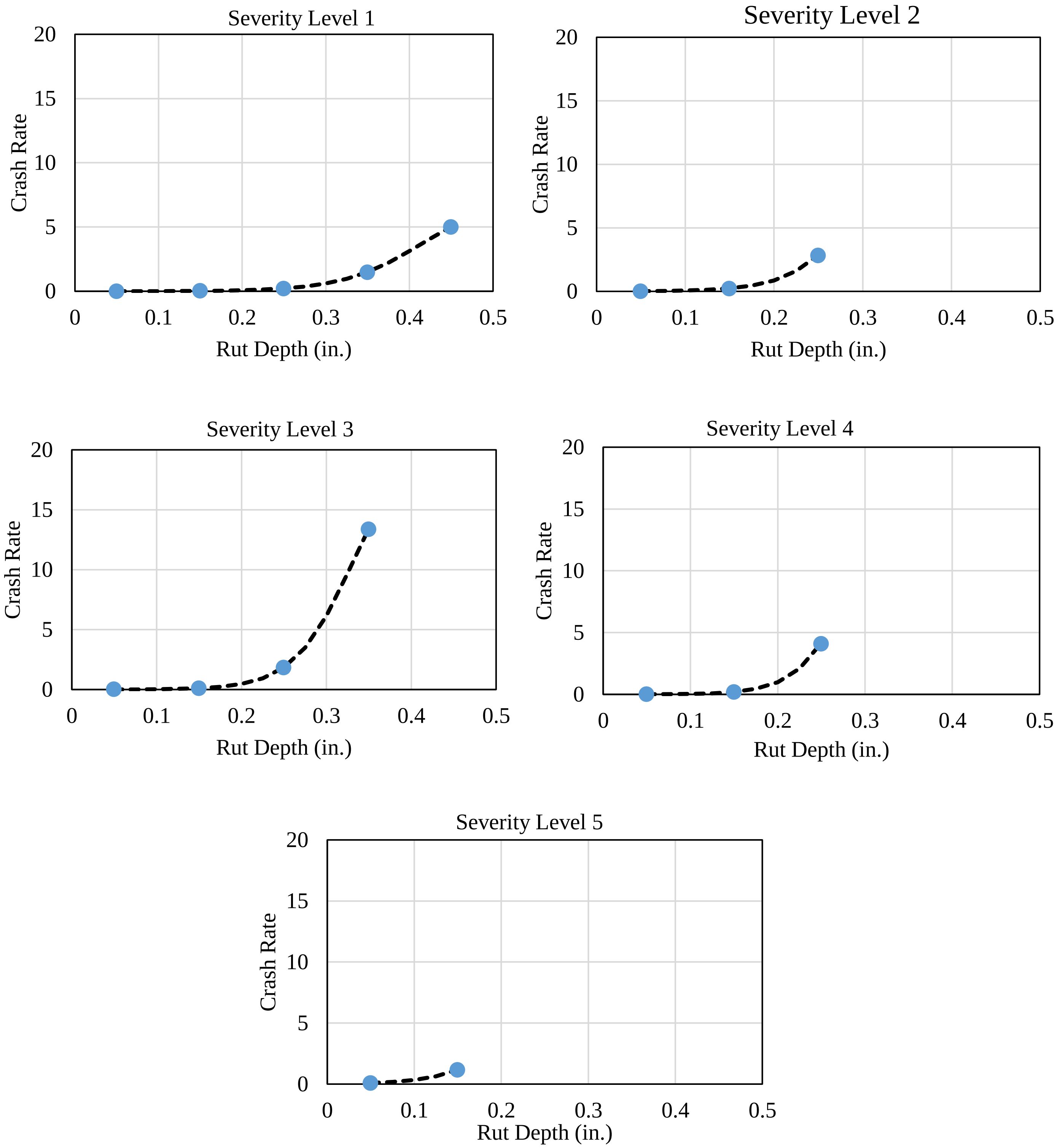


Figure 4.10. Relationship between crash rate and rut depth for severity levels 1-5 (Arizona 2014)

4.3.2 North Carolina 2015

Figure 4.11 shows the relationship between crash rate and rut depth for all severity levels combined, while Figure 4.12 shows similar relationships for severity levels 1-5. Similar to the Arizona results, all graphs show that crash rate does not basically increase up to a certain rut depth value, above which crash rate largely increase. This phenomenon suggests that if the rut depth value is kept below a certain value, crash rate can be decreased.

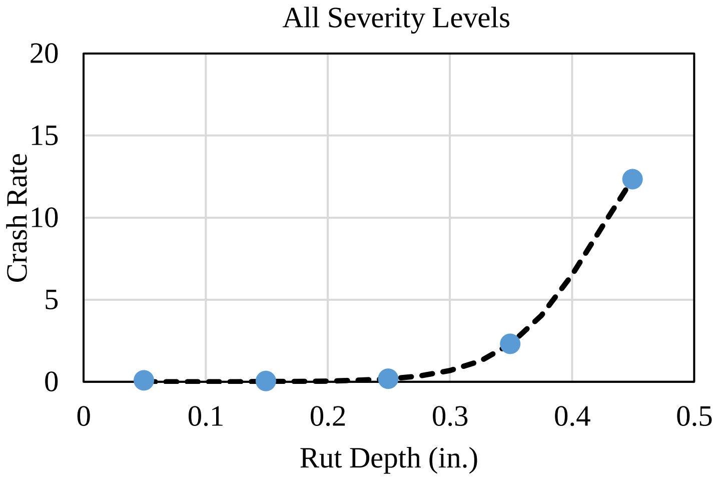


Figure 4.11. Relationship between crash rate and rut depth for all severity levels combined (North Carolina 2015)

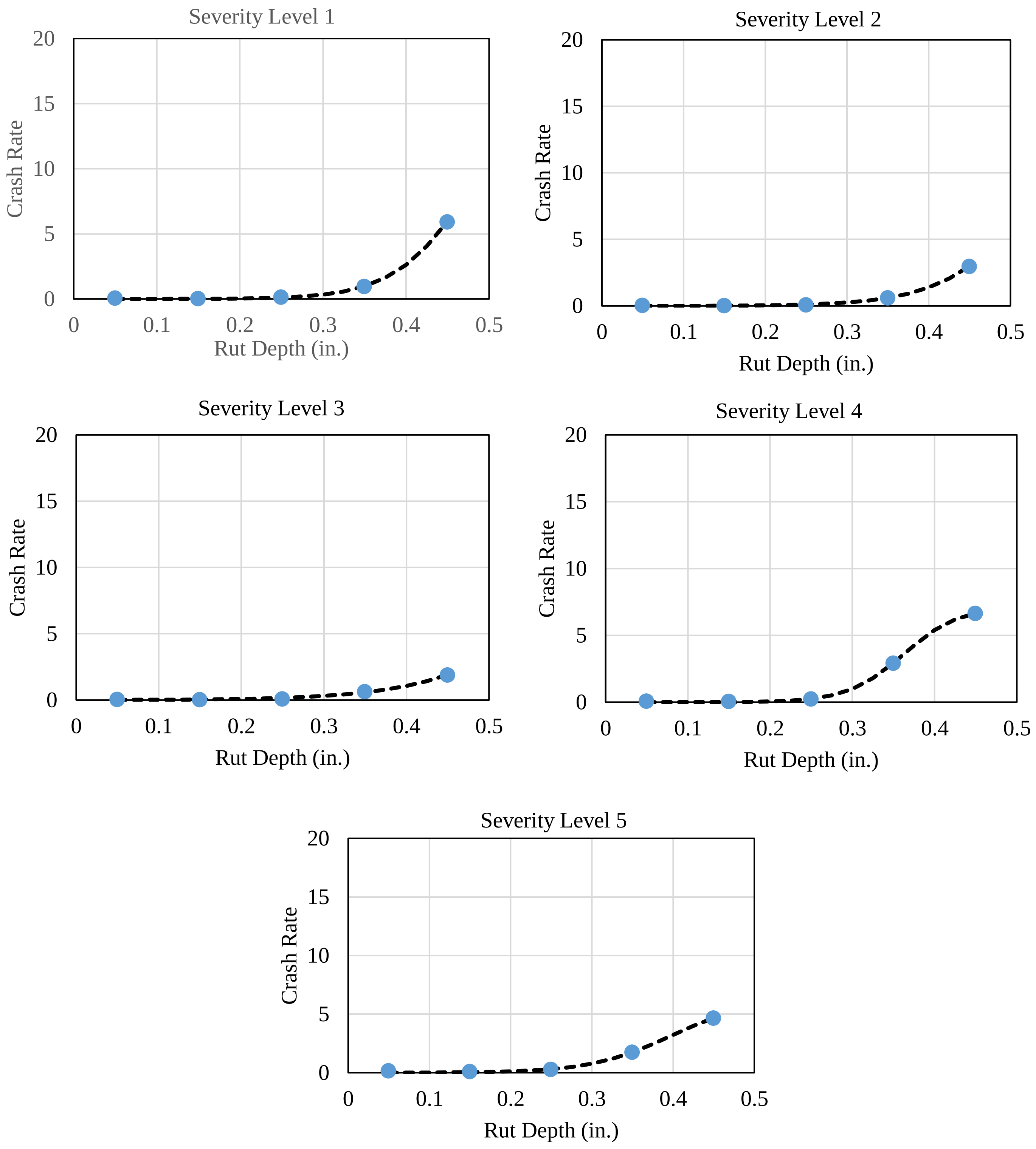


Figure 4.12. Relationship between crash rate and rut depth for severity levels 1-5 (North Carolina 2015)

4.3.3 Maryland 2014

As indicated earlier, the number of crashes used for analysis for the state of Maryland is considerably lower than the other states due to the fact that data obtained do not cover the whole state since the rest of crash data are not publicly available. Therefore, the crash rates used in this study do not represent the actual crash rates of the state of Maryland. They were used in this study only to study there trend with ride quality data, but not to show the actual crash rate values.

Figure 4.13 shows the relationship between crash rate and IRI values for all severity levels combined, while Figure 4.14 shows similar relationships for severity level 1 and levels 2-4 combined. As indicated earlier, no fatality crashed were reported in this sample of data in Maryland. Similar to the Arizona and North Carolina results, all graphs show that crash rate does not mostly increase up to a certain rut depth value, above which crash rate starts to increase. This phenomenon suggests that if the rut depth value is kept below a certain value, crash rate can be minimized.

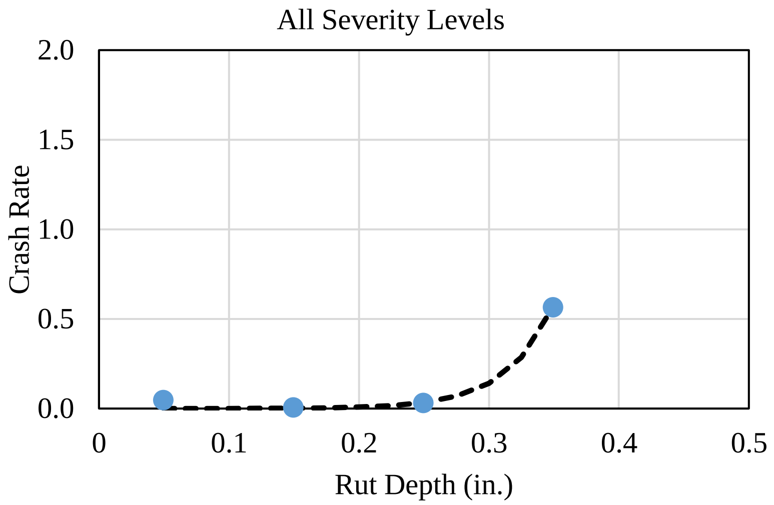


Figure 4.13. Relationship between crash rate and rut depth for all severity levels combined (Maryland 2014)

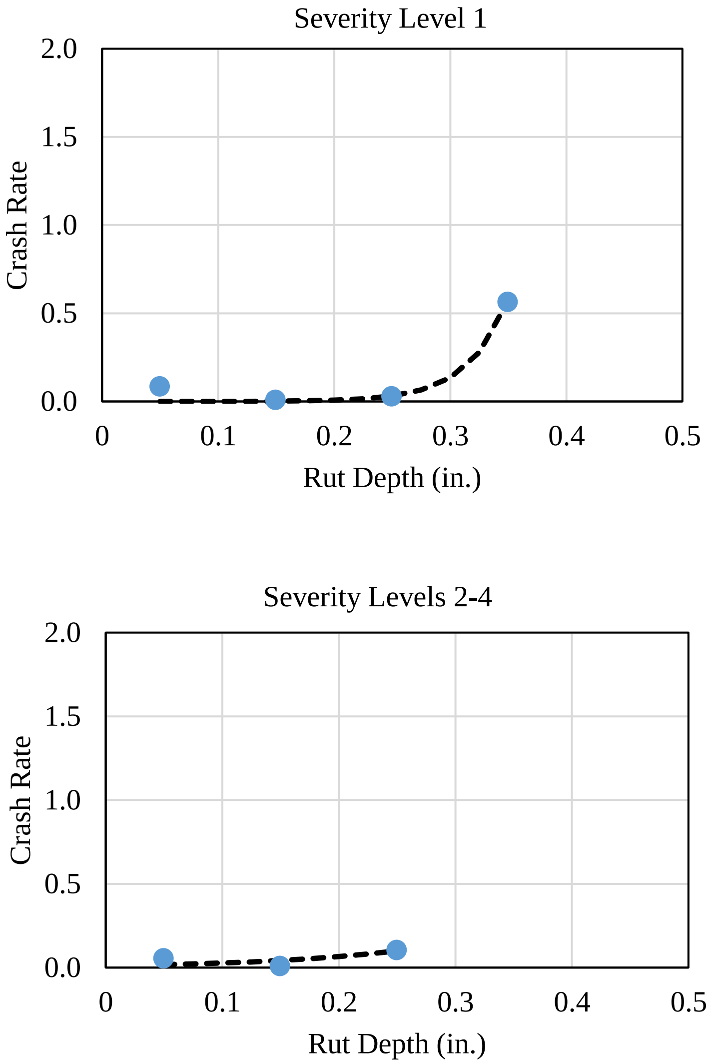


Figure 4.14. Relationship between crash rate and rut depth for severity level 1 and levels 2-4 (Maryland 2014)

4.4 Critical Safe Pavement Condition

As indicated earlier, the crash rate does not essentially increase with the increase in IRI up to a certain critical value, after which the crash rate begins to increase. Similarly, the crash rate does not basically increase with the increase in rut depth up to a certain critical value, after which the crash rate starts to increase. Therefore, it is important to objectively define the critical IRI and rut depth values below which crashes can be kept to a small rate. If a transportation agency maintains its pavement condition so that the IRI and rut depth values do not exceed these critical values, accidents can be reduced.

Using the data available in this study, several methods were tried to determine critical IRI and rut depth values below which crash rate can be kept to a minimum value. An objective definition of these critical values would be better than a subjective one. Since sigmoidal functions were used in this study to relate the crash rate to both IRI and rut depth values, the critical IRI and rut depth values were determined as the intercept of a line tangent to and extending from the inflection point of the sigmoidal function back to zero as shown in Figure 4.15. The inflection point was located by taking the second derivative of the sigmoidal function of each case (Equation 4.1). The tangent was determined by taking the first derivative of the sigmoidal function at the inflection point. The intersection of the tangent line with the x-axis was selected as the critical IRI or rut depth.

In a few cases, the curves ended below the inflection point because of the low accident data available. In such cases, the procedure for determining the critical IRI and rut depth values were kept the same for consistency. The amount of error involved in in these cases were within the acceptable rounding error of IRI and rut depth values.

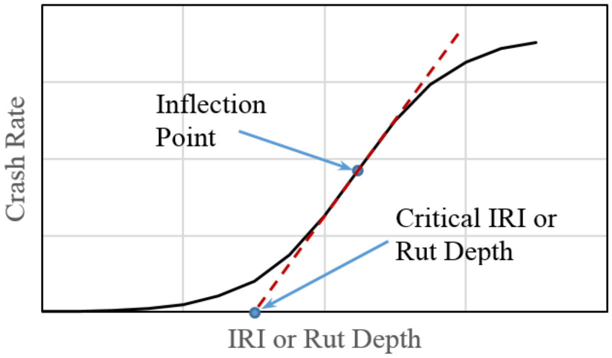


Figure 4.15. Determination of critical IRI or rut depth to minimize crash rate

The critical IRI and rut depth values were determined for the cases of all severity levels combined for each state as shown in Tables 4.4 and 4.5. The tables show that the average of critical IRI value is 210 inches/mile, whereas the average critical rut depth value is 0.4 inches. This is a key conclusion that provides empirically derived thresholds for safety concerns. If a transportation agency keeps its road network below these critical pavement conditions, the crash rate would largely decrease.

The recommendation that safety can be improved by keeping roughness and rut depth below a certain critical level is in full agreement with the concept of pavement preventive maintenance. Studies show that if an agency applies maintenance treatments early in the age of the pavement, the pavement would stay in a good condition for a long time (Mamlouk and Zaniewski, 2001). Therefore, applying maintenance treatments such as chip seal, microsurfacing or thin overlay at early ages, not only would keep pavement in good condition for a long time, but also would make the road safer.

Table 4.4. Critical IRI values in different cases to minimize crash rate

State	Year	Critical IRI (in./mile)
Arizona	2013	192
	2014	152
North Carolina	2015	268
Maryland	2014	208
Average (rounded)		210

Table 4.5. Critical rut depth values in different cases to minimize crash rate

State	Year	Critical Rut Depth (in.)
Arizona	2014	0.35
North Carolina	2015	0.35
Maryland	2014	0.4
Average (rounded)		0.4

5.0 SUMMARY AND CONCLUSIONS

Highway safety is a major priority for the public and for transportation agencies. Numerous amount of research is being carried out in order to improve highway safety and reduce crash rate. Pavement distresses directly affect ride quality, and indirectly contribute to driver distraction, vehicle operation, and accidents. The majority of previous studies dealing with the effect of pavement condition on safety are related to skid resistance, whereas limited knowledge is available on the effect of other pavement distresses on safety. This study investigates the effect of pavement ride quality measured by the international roughness index (IRI) and rut depth on accident rate. These pavement condition parameters have been collected from different sources to develop regression models to relate pavement condition to rate of accidents at different severity levels. One of the challenges of the research work was collecting the data from various sources, and obtaining common grounds for data matching and integration.

5.1 Summary

Analysis was performed on highways in the states of Arizona, North Carolina and Maryland. The data were obtained between the years 2013 and 2015. States and year of analysis have been selected depending on data availability and varying geographical locations and climate conditions. Two main types of data were collected: crash data from the accident records and IRI and rut depth data from the pavement management system databases. Data were brought together from the national Highway Performance Monitoring System (HPMS) public data release, Arizona Department of Transportation (ADOT) database, and open source crash data available from the three states. Complete accident and pavement condition records were obtained from Arizona and North Carolina. However, data obtained from Maryland did not cover the whole state since a portion of crash data was not publicly available. Therefore, the Maryland crash rates were used to study their trend with IRI data, but not necessarily to show the actual crash rate values.

The specific data items that were used in the study were crash frequency and severity, traffic volume (expressed in terms of AADT), IRI, and rut depth. Geographical locations, i.e., road name and milepost or latitude and longitude were used as the common criteria for matching the crash data with Pavement Management Systems data in North Carolina and Maryland. SQL queries and ArcGIS were used to integrate the data and obtain the results. During the initial screening of the data, the crash occurrences that state other factors, such as weather condition, as the major cause of the crash were removed prior to the analysis. However, in most cases the contributing factor for crash occurrence was generally not reported. In addition, data points that fall outside of the typical range were removed from the analysis. One mile segments are used for analysis and 1 year is taken as the period of analysis.

For each state and each crash severity level, the IRI and rut depth values were broken down to categories of 50 inches/mile and 0.5 inches, respectively. For each category, the crash rate was calculated using the U.S. Department of Transportation method, which is average number of accidents per vehicle per mile per year multiplied by 100,000,000. The variations of crash rate with average IRI and average rut depth were investigated. Sigmoidal function regression analysis is performed to study the relationship between crash rate and IRI and rut depth values. Individual analysis has been conducted for all crash severity levels combined and for each severity level separately. Critical IRI and rut depth values below which crashes can be kept to a small rate were determined.

5.2 Conclusions

The following conclusions can be drawn from the results of this study.

1. IRI and rut depth values of crash and non-crash segments in each state-year combination were close to each other. This suggests that ride quality and rutting are not the only factors affecting number of crashes, but possibly in combination with other factors such as traffic volume, other pavement distresses, and others.
2. There is a unique relationship between IRI and crash rate in all cases, indicating that crash rate does not basically increase up to a certain IRI value, above which crash rate starts to increase. This phenomenon occurred for individual crash severity levels as well as for all crash severity levels combined.
3. Similar to ride quality, crash rate does not essentially increase up to a certain rut depth value, above which crash rate starts to increase. This phenomenon occurred for individual crash severity levels and for all crash severity levels combined.

4. The critical IRI values above which crash rate starts to increase varied from one state to another because of the difference in the measurements in each state due to factors such as measurement equipment, data processing methods, sampling method, or number of runs of measuring devices. The average critical IRI value for all three states above which crash rate starts to increase is 210 inches/mile.
5. The average critical rut depth value above which crash rate starts in increase was almost the same for all three states with an average value of 0.4 inches.

Note that the average threshold values of IRI and rut depth concluded in this study need to be used with caution because of the differences in measurements between states as stated above. It should be also noted that crashes are rare and uncommon events. Therefore, more studies with large amounts of crash data are needed to confirm the results of this study. Future studies need to combine the effect of IRI and rut depth with other contributing factors such as human behavior, vehicular malfunction, environmental factors, and roadway geometry.

6.0 RECOMMENDATIONS FOR FUTURE RESEARCH

The following recommendations for future research are derived.

1. The study found that ride quality and rutting affect crash occurrences. However, during the study, other contributing factors like highway geometric conditions, weather condition, vehicle speed, alcohol/drug usage while driving, mobile phone usage, etc., have not been considered. Using other major contributing factors, along with pavement condition and developing a multi-factor regression model would help obtaining more comprehensive results and identifying the cause of crashes more accurately.
2. Cost analysis can be performed to evaluate the total cost of the crashes and compare it with the cost required for pavement maintenance. This would allow the highway agencies to take a more informed decision on highway maintenance programs. Maps or mobile apps can also be developed to inform the driver about the crash prone areas with poor pavement condition in order to warn drivers to be more careful in such areas.
3. The policy followed by the agency has a direct impact in terms of economic cost. For example, consider two scenarios; one in which the policy of the state is to maintain the pavement when the threshold identified here is reached and one that defers maintenance. Presumably the first strategy would result in more agency cost in terms of maintenance, but the theory is that accident rates would decrease thereby lowering society's cost and lowering user costs from delays caused by the accidents. A life-cycle cost analysis for the deferred-maintenance strategy and for the one that prioritizes maintenance on safety would determine the most cost-effective strategy. Different permutations can be evaluated to determine the effect on the results.

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APPENDIX A
CRASH RATE VS. IRI DATA TABLES

1. Arizona 2013- All Severities

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0	49	24.5	30159.7	3.0	499.0	0.06
50	99	74.5	42290.9	6.5	1386.0	0.03
100	149	124.5	15409.3	2.3	319.0	0.13
150	199	174.5	13381.4	2.2	54.0	0.85
200	249	224.5	7110.4	1.4	9.0	6.18

2. Arizona 2013- Severity 1

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash rate
0	49	24.5	35193.1	2.9	428	0.05
50	99	74.5	48094.8	5.5	1147	0.03
100	149	124.5	16985.3	1.9	254	0.12
150	199	174.5	14805.6	1.9	44	0.78
200	249	224.5	9725.7	1.3	3	12.52

3. Arizona 2013- Severity 2

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash rate
0	49	24.5	69827.9	1.8	107	0.07
50	99	74.5	92290.7	3.2	429	0.02
100	149	124.5	25944.0	1.5	63	0.25
150	199	174.5	17293.0	1.2	12	1.54

4. Arizona 2013- Severity 3

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash rate
0	49	24.5	51684.8	1.5	171	0.05
50	99	74.5	73711.8	2.2	531	0.02
100	149	124.5	18117.1	1.2	98	0.18
150	199	174.5	14560.4	1.2	17	1.37
200	249	224.5	6534.7	1.3	3	18.63

5. Arizona 2013- Severity 4

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash rate
0	49	24.5	54760.6	1.1	42	0.13
50	99	74.5	90024.9	1.2	184	0.02
100	149	124.5	22062.1	1.0	27	0.46
150	199	174.5	28613.0	1.0	2	4.79

6. Arizona 2013-Severity 5

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash rate
0	49	24.5	40080.9	1.0	32	0.21
50	99	74.5	67397.9	1.0	70	0.06
100	149	124.5	12512.3	1.1	12	1.98
150	199	174.5	11057.5	1.0	2	12.39
200	249	224.5	15575.0	1.0	1	17.59

7. Arizona 2014-All Crashes

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0	49	24.5	35890.3	3.2	811	0.03
50	99	74.5	50360.7	6.9	1921	0.02
100	149	124.5	21785.3	3.7	404	0.12
150	199	174.5	16228.7	3.9	78	0.84
200	249	224.5	13649.7	1.9	16	2.43

8. Arizona 2014- Severity 1

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0	49	24.5	40545.9	2.9	702	0.03
50	99	74.5	56936.3	5.9	1613	0.02
100	149	124.5	46297.8	5.1	1321	0.02
150	199	174.5	18617.6	3.3	66	0.74
200	249	224.5	13455.3	1.4	13	2.17

9. Arizona 2014- Severity 2

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0	49	24.5	71656.4	1.8	199	0.03
50	99	74.5	98045.9	2.8	669	0.01
100	149	124.5	48306.9	2.5	81	0.17
150	199	174.5	37978.1	3.1	15	1.47
200	249	224.5	18655.3	1.3	3	6.53
250	299	274.5	15625.0	1.0	1	17.53

10. Arizona 2014- Severity 3

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0	49	24.5	58973.5	1.5	259	0.03
50	99	74.5	84239.1	2.2	769	0.01
100	149	124.5	36486.9	1.5	115	0.10
150	199	174.5	33942.8	1.8	17	0.87
200	249	224.5	13862.8	1.2	6	3.84

11. Arizona 2014- Severity 4

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0	49	24.5	68068.1	1.1	67	0.06
50	99	74.5	85684.9	1.1	232	0.02
100	149	124.5	20180.7	1.0	38	0.37

12. Arizona 2014-Severity 5

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0	49	24.5	45939.2	1.0	29	0.2
50	99	74.5	53041.5	1.0	57	0.1
100	149	124.5	66575.3	1.0	13	0.3
150	199	174.5	8041.3	1.0	6	5.7

13. North Carolina 2015– All Crashes

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0	49	24.5	36097.2	14.4	250	0.44
50	99	74.5	19060.2	9.1	3082	0.04
100	149	124.5	10780.9	5.7	1867	0.08
150	199	174.5	10838.5	5.1	437	0.29
200	249	224.5	12009.6	5.0	126	0.90
250	299	274.5	12597.5	4.6	36	2.80
300	349	324.5	6672.7	3.2	12	10.83
350	399	374.5	15440.0	1.8	6	5.42
400	449	424.5	16512.5	2.6	5	8.63

14. North Carolina 2015- Severity 1

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0	49	24.5	35456.6	9.8	319	0.24
50	99	74.5	19489.0	7.3	2846	0.04
100	149	124.5	12586.1	5.0	1366	0.08
150	199	174.5	10935.5	4.1	346	0.30
200	249	224.5	11663.4	4.1	110	0.88
250	299	274.5	13743.0	4.9	49	1.98
300	349	324.5	9726.2	3.7	17	6.14
350	399	374.5	17336.0	2.5	12	3.29
400	449	424.5	8496.4	2.8	14	6.42

15. North Carolina 2015- Severity 2

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0	49	24.5	42291.7	3.8	206	0.12
50	99	74.5	22524.1	3.2	1694	0.02
100	149	124.5	14184.5	2.5	799	0.06
150	199	174.5	12255.4	2.1	195	0.24
200	249	224.5	14109.0	2.1	58	0.72
250	299	274.5	12829.1	2.2	22	2.12
300	349	324.5	13298.3	3.4	14	5.05
350	399	374.5	14548.8	1.4	8	3.24

16. North Carolina 2015– Severity 3

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0	49	24.5	48309.9	2.1	126	0.09
50	99	74.5	24033.6	1.8	1025	0.02
100	149	124.5	15724.8	1.5	388	0.07
150	199	174.5	13047.2	1.4	97	0.29
200	249	224.5	16383.9	1.4	37	0.62
250	299	274.5	8182.8	1.0	9	3.72
300	349	324.5	11614.2	1.8	5	8.49
350	399	374.5	12669.0	2.0	6	7.21
400	449	424.5	11827.8	1.2	6	4.50

17. North Carolina 2015– Severity 4

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0	49	24.5	53834.7	1.1	33	0.17
50	99	74.5	25472.7	1.1	204	0.06
100	149	124.5	17248.1	1.0	73	0.22
150	199	174.5	12452.7	1.0	18	1.22
200	249	224.5	12411.5	1.0	8	2.76

18. North Carolina 2015– Severity 5

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0	49	24.5	45827.4	1.1	27	0.25
50	99	74.5	24846.0	1.1	148	0.08
100	149	124.5	22892.7	1.1	62	0.21
150	199	174.5	17725.1	1.0	9	1.72
200	249	224.5	8566.2	1.0	6	5.33
250	299	274.5	15192.5	1.0	2	9.02
350	399	374.5	25750.0	1.0	1	10.64

19. Maryland 2014– All Crashes

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0.0	49.0	24.5	113589.6	1.2	9	0.03
50.0	99.0	74.5	95568.6	1.5	45	0.01
100.0	149.0	124.5	72230.9	1.8	26	0.03
150.0	199.0	174.5	69236.4	1.8	18	0.04
200.0	249.0	224.5	92717.1	2.4	10	0.07
250.0	299.0	274.5	59553.6	1.2	5	0.11
300.0	349.0	324.5	69394.3	3.0	3	0.39
350.0	399.0	374.5	71315.0	1.0	1	0.38
400.0	449.0	424.5	36326.0	1.0	2	0.38
450.0	499.0	474.5	43412.0	1.0	1	0.63

20. Maryland 2014– Property Damage

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0.0	49.0	24.5	106822.6	1.0	8.0	0.03
50.0	99.0	74.5	97171.7	1.7	30.0	0.02
100.0	149.0	124.5	77354.0	1.9	20.0	0.03
150.0	199.0	174.5	63751.1	1.7	16.0	0.05
200.0	249.0	224.5	98237.3	2.3	7.0	0.09
250.0	299.0	274.5	59553.6	1.2	5.0	0.11
300.0	349.0	324.5	71315.0	2.5	2.0	0.48
400.0	449.0	424.5	36326.0	1.0	2.0	0.38
450.0	499.0	474.5	43412.0	1.0	1.0	0.63

21. Maryland 2014– Physical Injury

Start IRI	End IRI	Average IRI	AADT	Average Crashes	Number of miles	Crash Rate
0	49	24.5	167725.0	1.5	2.0	0.12
50	99	74.5	99043.1	1.0	17.0	0.02
100	149	124.5	69486.5	1.1	10.0	0.04
150	199	174.5	84178.0	1.0	5.0	0.07
200	249	224.5	85710.0	1.3	6.0	0.07
300	349	324.5	68434.0	2.0	2.0	0.40
350	399	374.5	71315.0	1.0	1.0	0.38

APPENDIX B
CRASH RATE VS. RUT DEPTH DATA TABLES

1. Arizona - 2014 - All Crashes

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	38035.6	5.0	1571	0.02
0.1	0.199	0.1495	29031.9	3.7	252	0.14
0.2	0.299	0.2495	26268.6	1.9	16	1.26
0.3	0.399	0.3495	20501.0	1.5	2	10.02

2. Arizona – 2014 – Severity 1

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	22197.3	2.2	3541	0.01
0.1	0.199	0.1495	17120.6	1.5	639	0.04
0.2	0.299	0.2495	14828.8	0.6	53	0.21
0.3	0.399	0.3495	11308.9	0.4	7	1.48
0.4	0.499	0.4495	13679.5	0.5	2	5.01

3. Arizona – 2014 – Severity 2

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	83410.4	2.6	388	0.02
0.1	0.199	0.1495	64242.2	2.4	44	0.23
0.2	0.299	0.2495	32230.0	1.0	3	2.83

4. Arizona – 2014 – Severity 3

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	65310.0	2.1	513	0.02
0.1	0.199	0.1495	42221.2	1.5	89	0.11
0.2	0.299	0.2495	35897.8	1.2	5	1.83
0.3	0.399	0.3495	20501.0	1.0	1	13.36

5. Arizona – 2014 – Severity 4

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	78873.6	1.1	150	0.03
0.1	0.199	0.1495	47428.7	1.0	31	0.19
0.2	0.299	0.2495	50096.0	1.5	2	4.10

6. Arizona – 2014 – Severity 5

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	61691.8	1.0	47	0.09
0.1	0.199	0.1495	21278.6	1.0	11	1.17

7. North Carolina 2015– All Crashes

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	19789.2	7.7	1486	0.07
0.1	0.199	0.1495	15579.8	7.9	3521	0.04
0.2	0.299	0.2495	14261.7	7.4	807	0.18
0.3	0.399	0.3495	11147.8	8.7	93	2.30
0.4	0.499	0.4495	11246.2	7.6	15	12.34

8. North Carolina 2015– Severity 1

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	21353.9	6.4	1303	0.06
0.1	0.199	0.1495	17343.9	6.9	2946	0.04
0.2	0.299	0.2495	14878.2	5.7	765	0.14
0.3	0.399	0.3495	11712.7	5.2	126	0.96
0.4	0.499	0.4495	13314.3	6.0	21	5.93

9. North Carolina 2015– Severity 2

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	25181.9	3.1	787	0.04
0.1	0.199	0.1495	20239.0	3.1	1682	0.02
0.2	0.299	0.2495	17364.4	2.5	495	0.08
0.3	0.399	0.3495	12044.0	2.2	83	0.61
0.4	0.499	0.4495	8639.1	1.5	16	2.97

10. North Carolina 2015– Severity 3

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	25166.7	1.7	449	0.04
0.1	0.199	0.1495	22845.8	1.7	995	0.02
0.2	0.299	0.2495	21104.5	1.6	243	0.09
0.3	0.399	0.3495	15521.9	1.6	46	0.63
0.4	0.499	0.4495	12019.3	1.1	13	1.89

11. North Carolina 2015- Severity 4

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	31492.9	1.0	105	0.09
0.1	0.199	0.1495	21455.2	1.0	194	0.07
0.2	0.299	0.2495	31406.6	1.0	37	0.24
0.3	0.399	0.3495	9385.4	1.0	10	2.92
0.4	0.499	0.4495	20600.0	1.0	2	6.65

12. North Carolina 2015– Severity 5

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	30129.1	1.1	69	0.15
0.1	0.199	0.1495	23843.1	1.1	140	0.09
0.2	0.299	0.2495	25645.2	1.1	41	0.28
0.3	0.399	0.3495	17510.0	1.0	9	1.74
0.4	0.499	0.4495	29406.5	1.0	2	4.66

13. Maryland 2014- All Crashes

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	86353.3	2.0	13	0.05
0.1	0.199	0.1495	84592.3	1.6	81	0.01
0.2	0.299	0.2495	96511.5	1.7	15	0.03
0.3	0.399	0.3495	72712.5	3.0	2	0.57

14. Maryland 2014– Property Damage

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	105029.0	2.3	7	0.09
0.1	0.199	0.1495	81150.4	1.7	60	0.01
0.2	0.299	0.2495	102408.9	1.4	13	0.03
0.3	0.399	0.3495	72712.5	3.0	2	0.57

15. Maryland 2014– Physical Injury

Start Rut depth	End rut depth	Average rut depth	AADT	Average Crashes	Number of miles	Crash Rate
0	0.099	0.0495	76839.1	1.3	8	0.1
0.1	0.199	0.1495	90027.8	1.0	31	0.0
0.2	0.299	0.2495	112952	1.8	4	0.1