Preliminary Results towards Developing Thresholds for Pavement Condition Maintenance: Safety Perspective

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Abstract

This paper focuses on examining the relationship between the International Roughness Index (IRI) and crashes to compare thresholds from a safety perspective with fuel efficiency perspective and pavement condition categories. Findings from the literature review, profile elevations captured using a laser profilometer along two test corridors in the State of North Carolina, United States (first one with concrete pavement and the second one with asphalt pavement), traffic volume from travel survey maps, and crash data maintained by the North Carolina Department of Transportation (NCDOT) were used for analysis and identification of preliminary thresholds from the safety perspective for pavement maintenance. Profile elevation data was processed to compute IRI values for each 100-m (330-ft) section along each selected corridor by direction. Crashes (all and under wet-pavement conditions) were identified for each section and added to the database. Scatter plots were generated to observe the trends in the number of all and wet-pavement crashes per mile by IRI. The average number of all crashes per section, wet-pavement crashes per section, all crashes per million vehicle miles travelled (MVMT) and wet-pavement crashes per MVMT were also computed for each corridor. Results obtained indicate that targeting and maintaining lower IRI to improve fuel efficiency may yield similar benefits from a safety perspective. Based on analysis using data for the considered corridors, they do not seem to vary by pavement type.

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1. Introduction

Road characteristics, vehicle characteristics, traffic composition, driver behaviour, and temporal variations, in general, have a bearing on fuel consumption, vehicle emissions and safety on roads. It has been estimated that, in 2011, the United States consumed about 131 billion gallons of gasoline, a daily average of 360 million gallons (U.S. EIA, 2012). There are about 254 million vehicles that use gasoline and travel, on average, more than 18,560 km/year (11,600 mi/year). An average passenger car is estimated to consume 0.044 gallons/mi (0.103 L/km) and emit 362.9 grams (0.8 pounds) of Carbon Dioxide, 1.5 grams (0.0033 pounds) of Nitrogen Oxide, 22 grams (0.0485 pounds) of Carbon Monoxide, and 2.9 grams (0.0064 pounds) of Hydrocarbons. On the other hand, an average light truck is estimated to consume 0.065 gallons/mi (0.153 L/km) and emit 544.3 grams (1.2 pounds) of Carbon Dioxide, 1.9 grams (0.0042 pounds) of Nitrogen Oxide, 29 grams (0.0639 pounds) of Carbon Monoxide, and 3.7 grams (0.0082 pounds) of Hydrocarbons (U.S. EPA, 1997).

Crash statistics published by the National Highway Traffic Safety Administration (NHTSA) indicate that over 32,800 people were killed and 2.24+ million injured in road crashes, in the United States, during 2010. Worldwide, economic losses due to road crashes exceed US $500 billion annually (WHO, 2013). Larson and Smith (2010) estimate that nearly 30% of annual highway fatalities are due to poor pavement conditions on roads.

Factors related to pavement type (e.g., concrete, asphalt, etc.), travel speed, weather/environment, wheel (vehicle) load, tire characteristics, and traffic over time influence pavement conditions (Kummer, 1966; Sandberg, 1997; Wallman et al., 2001). Analyzing and understanding the relationship between pavement condition, factors that affect pavement condition, and fuel consumption, emissions and crashes may help identify fuel inefficient and unsafe pavement sections with inadequate pavement condition (say, below a certain International Roughness Index, IRI, threshold value) and proactively apply remedial treatments. The IRI threshold values from a fuel consumption perspective may be equivalent to those obtained from emissions but may be significantly different from a safety perspective. They also may not be applicable for directional textures or textures of vastly different type. There is, therefore, a need to explore these relationships, examine the relationship between IRI and crashes, define IRI thresholds from safety perspective, and compare them with fuel efficiency perspective.

2. Brief Discussion on Technologies to Capture Pavement Condition Data

The widespread use of digital technologies, combined with rapid sensor advancements, has resulted in a paradigm shift in geospatial technologies around the end of last millennium (Greiner-Brzezinska et al., 2004). Digital images from airborne and satellite platforms and Unmanned Aerial Vehicle (UAV) are routinely used for intelligence surveillance. Terrain and pavement data, on the other hand, are better captured using optical sensors, laser profilometers, and laser scanners (includes Light Detection And Ranging [LiDAR]). Elevation correlations can be captured using laser profilometers, while cross slope correlations can also be captured using LiDAR to meet current road profiling requirements (Chang et al., 2006). Collecting pavement condition data using technologies such as optical sensors, inertial laser profilometers or mobile laser scanners reduces traffic delays as they can be carried out with minimal or no interruption to traffic flow. These technologies also lower risk to crew collecting data.

Laser profilometers are being extensively used in recent years to collect elevation details of pavement profile to determine a variety of pavement characteristics including pavement roughness, rutting, ride quality, and pavement macrotexture. As an example, the staff of North Carolina Department of Transportation (NCDOT) collects profile data on a two-year cycle along most highways in the State of North Carolina, United States. Procedures based on standards set by American Society for Testing and Materials (ASTM) are typically adopted to calculate pavement roughness, rutting, ride quality, and pavement macrotexture using the raw profile elevation data collected from the laser profilometer (example, ASTM, 2003). Recently, Olson and Chin (2012) compared
pavement roughness from terrestrial laser scanners with those obtained from inclinometers and inertial profilometers and found that the results are accurate and similar.

The Federal Highway Administration (FHWA) of the United States Department of Transportation (USDOT) categorizes the pavement condition as “good” if the measured IRI is less than 1.5 m/km (95 in./mi). It is considered as “acceptable” if IRI is less than 2.7 m/km (170 in./mi) but greater than 1.5 m/km (95 in./mi). IRI values exceeding the “acceptable” limit are considered as “unacceptable” (U.S. DOT, 2012).

3. Pavement Condition and Fuel Consumption

Over half of the air pollution in the United States is caused by the transportation sector, mostly automobiles (U.S. EPA, 2012). It is also generally opined that the emissions from vehicles are linearly proportional to the fuel consumption. Although the gallon per unit distance is increasing due to advancements in the automobile industry and Corporate Average Fuel Economy (CAFE) standards, the fuel consumption continues to increase with increasing vehicle kilometres (or miles) of travel. The consumption of fuel also depends on vehicle characteristics such as age, make/model and other operating characteristics of the vehicle.

The properties such as pavement roughness, skid resistance, rolling resistance, and noise are mainly influenced by road surface texture and tire tread. The interaction between the tire and the road surface provides grip to facilitate braking and vehicle maneuvering. At the same time, it also effects fuel consumption and emissions generated by the vehicle.

Sayers (1996) found that a decrease in pavement roughness by 1 m/km (63.4 in./mi) results in about 1 percent decrease in the tire wear for passenger cars. It was estimated that a decrease in IRI by 1 m/km (63.4 in./mi) will save 321 million dollars per year. The study by Sayers (1996) shows that there is no effect because of roughness up to IRI of 3 m/km (~190 in./mi). Beyond this range, an increase in IRI up to 4 m/km (253.4 in./mi) will increase repair and maintenance cost by 10% for passenger cars and heavy trucks. At IRI of 5 m/km (316.8 in./mi), this increase is up to 40% for passenger cars and 50% for heavy trucks.

Amos (2006) performed a study for the Missouri Department of Transportation (MoDOT) and found that a 53% improvement in smoothness resulted m/km (61 in./mi) and make the pavement smooth.

Ko (2010) measured fuel consumption on two paved roads of different IRI with medium (2,000 cc) and large (3,300 cc) cars in the speed range of 40-100 kmph (25-62.5 mph). A global positioning system (GPS) sensor was used to measure the speed while the fuel consumption was measured by processing the voltage signal of fuel injector of vehicle. Their study concluded that fuel consumption (expressed in L/100 km) of medium and large passenger cars increases 7 times fast of the increase of IRI around 3.5 m/km (221.8 in./mi) in the speed range of 40-100 kmph (25-62.5 mph). Likewise, in a presentation made by researchers of the National Center for Asphalt Technology at Auburn University, results shown indicate a 4.5% reduction in fuel consumption with a 10% decrease in IRI (NCAT, 2008).

Chatti and Zabaar (2012) demonstrated that vehicle operating costs (gasoline consumption and associated emissions) increase with pavement roughness and deterioration for all classes of vehicles and types of pavements investigated. The most important cost components affected by pavement roughness (measured typically using the IRI) are fuel consumption followed by repair and maintenance, then tire wear. Their study indicates that an increase in IRI of 1 m/km (63.4 in./mi) will increase the fuel consumption of passenger cars by 2% irrespective of speed. The effects are higher for heavy trucks.

Overall, past researchers observed that the relationship between IRI and fuel consumption is generally linear. Maintaining lower IRI ("good" pavement condition) will decrease fuel consumption and lead to economic benefits. The percent reduction in fuel consumption or improvement in fuel efficiency due to smooth pavement (reduction in IRI) ranges from 1% to 5%.
4. Pavement Condition and Safety

Adequate pavement roughness provides safe braking and stopping of vehicles especially at intersections and along curves under inclement weather conditions. Inadequate IRI leads to an increase in the number of crashes. Giles et al. (1962), McCullough and Hankins (1966), Rizenbergs et al. (1972), Schulze et al. (1976), Wallman and Astrom (2001), Bray (2002), and Murad et al. (2007) have studied the effect of pavement friction and associated roughness on crashes (in particular, wet-pavement crashes). Results from these studies generally indicate that wet-pavement crashes increase significantly as the pavement friction decreases. The risk of getting involved in skidding-related or wet-pavement crashes increase rapidly when Skid Number is below 40, while the risk is low when Skid Number is above 60.

The effect of pavement texture, which is a part of pavement skid resistance, has also been reported in skid resistance studies as early as in the seventies (e.g., Moore and Humphreys, 1972). Pavement texture, in particular, was found to be a primary factor affecting skid resistance at speeds over 64 kmph (40 mph) (Stroup-Gardiner et al., 2001). Rizenbergs et al. (1972), Schulze et al. (1976), Gandhi et al. (1991), and Hall Jr. et al. (2009) are example studies that discussed the relationship between pavement skid resistance and crashes.

Pulugurtha et al. (2010) concluded that maintaining pavement macrotexture greater than or equal to 1.524 mm (0.06 in.) as a threshold limit would possibly reduce crashes and provide safe transportation to road users on highways with asphalt pavements. On the other hand, maintaining pavement macrotextutre greater than or equal to 2.032 mm (0.080 in.) on tinned concrete pavements and greater than or equal to 1.016 mm (0.040 in.) on asphalt pavements would reduce crashes and enhance safety through improved braking performance on Interstates (Pulugurtha et al., 2012). However, IRI thresholds to maintain and manage pavements from a safety perspective were not identified or widely discussed in the past.

4.1. Method to Examine the Relationship between IRI and Crashes

The method adopted to examine the relationship between IRI and crashes to identify thresholds from safety perspective in this research is as follows.

Two Interstate (freeway or national highway) study corridors (I-40 in Durham County and I-40 in Pender County) in the State of North Carolina were selected to gather data and conduct an analysis. Table 1 summarizes the characteristics of the two study corridors selected for this research. While I-40 in Durham County is tinned (small grooves of specified dimension) concrete pavement, I-40 in Pender County is asphalt pavement. I-40 in Durham County was re-paved a couple of years before the study period, while I-40 in Pender County was not re-paved for more than a decade before the study period. Access to these corridors is controlled through ramps.

<table>
<thead>
<tr>
<th>Corridor</th>
<th>Direction</th>
<th># Lanes</th>
<th>Pavement Type</th>
<th>Length</th>
<th>Daily Traffic Volume</th>
<th># Crashes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fatal</td>
</tr>
<tr>
<td>I-40 in Durham County</td>
<td>Eastbound</td>
<td>3</td>
<td>Tinned concrete</td>
<td>15.8 km</td>
<td>101,660</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Westbound</td>
<td></td>
<td></td>
<td>(9.9 mi)</td>
<td></td>
<td>218</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>704</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>925</td>
</tr>
<tr>
<td>I-40 in Pender County</td>
<td>Eastbound</td>
<td>2</td>
<td>Asphalt</td>
<td>41.0 km</td>
<td>21,760</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Westbound</td>
<td></td>
<td></td>
<td>(25.6 mi)</td>
<td></td>
<td>214</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>677</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>895</td>
</tr>
</tbody>
</table>

* PDO is property damage only.

Profile elevations were collected for right and left wheel paths of outside lane using a laser road profiler (with 2 accelerometers and 3 height sensors) manufactured by International Cybernetics Corporation.

Each study corridor (example, I-40 eastbound in Durham County, North Carolina) was divided into approximately 100-m (330-ft) sections of equal length. IRI was determined with the help of Profile Viewing and
Analysis Software (ProVAl 2.7). This software, developed by the Transtec Group, is an engineering software application to view and analyze pavement profiles. A moving average filter of 250 was applied to compute IRI for each section. Using this filter, the average elevation of all the points under the length of each section is computed.

In the next step, crash data obtained from NCDOT were processed to identify the number of crashes on each study section in each direction. The identification of crashes in each section was based on the milepost information (location marker on roads) for each crash record in the crash database. The number of wet-pavement crashes for each study section in each direction was also determined.

The computed IRI and crash data were tied for each section to study the relationship between the two variables. In addition, million vehicle miles travelled (MVMT) as a function of traffic volume from travel survey maps and length was also collected for each section by direction and added to the database. Traffic composition and characteristics of vehicles using each section are not available in the travel survey maps for use in the analysis.

Scatter plots were generated and average values of different measures were computed as the last step to examine the relationship between IRI and crashes.

5. Analysis and Discussion

Profile data was collected during 2006 along the study corridors by the staff of NCDOT. Crash data was obtained from 2005 to 2007 from the same agency.

Traffic speed data was not available for the selected study corridors from 2005 to 2007. Anecdotal evidence, however, indicates that traffic speeds were not significantly different along the two corridors. The length and daily traffic volume varied while the total numbers of crashes were reasonably close along both the selected corridors. Very few fatal crashes were observed during the study period along the two study corridors.

Scatter plots were generated with the number of crashes per mile (= 1.6 km) for each section on Y-axis and the average IRI on x-axis. Figures 1 and 2 shows scatter plots for I-40 in Durham County and I-40 in Pender County, respectively.

The minimum and maximum IRI along I-40 in Durham County is 0.76 m/km (48 in./mi) and 3.3 m/km (209 in./mi), respectively. The number of all crashes per mile per section varied from 0 to 19 per year along this corridor. Data shows that 92 out of 184 sections (50%) with IRI less than 1.5 m/km (95 in./mi) have seen at least one crash per year along this corridor. Likewise, 75 out of 131 sections (57%) with IRI greater than 1.5 m/km (95 in./mi) have seen at least one crash per year along this corridor. Five out of these 131 sections have “unacceptable” IRI values (> 2.7 m/km or 170 in./mi). While 17 sections (9%) with computed IRI less than 1.5 m/km (95 in./mi) have seen at least one wet-pavement crash per year along this corridor, 22 sections (15%) with computed IRI greater than 1.5 m/km (95 in./mi) have seen at least one wet-pavement crash per year. Two out of the 22 sections have “unacceptable” IRI values (> 2.7 m/km or 170 in./mi).

The minimum and maximum IRI along I-40 in Pender County is 0.6 m/km (38 in./mi) and 2.5 m/km (161 in./mi), respectively. The number of all crashes per mile per section varied from 0 to 14 per year along this corridor. Data shows that 239 out of 719 sections (33%) with IRI less than 1.5 m/km (95 in./mi) have seen at least one crash per year along this corridor. Likewise, 39 out of 99 sections (39%) with IRI greater than 1.5 m/km (95 in./mi) have seen at least one crash per year along this corridor. While 45 sections (6%) with computed IRI less than 1.5 m/km (95 in./mi) have seen at least one wet-pavement crash per year along this corridor, 10 sections (10%) with computed IRI greater than 1.5 m/km (95 in./mi) have seen at least one wet-pavement crash per year.
Fig. 1. Scatter plots – I-40 in Durham County (tinned concrete pavement)
Fig. 2. Scatter plots – I-40 in Pender County (asphalt pavement)
While the scatter plots provided vital information (i.e., the number of crashes may increase as IRI increases), definite inferences could not be made about the relationship and thresholds. To further assist in assessing the relationship, the average number of all crashes per mile per section, the average number of wet-pavement crashes per mile per section, the average number of all crashes per MVMT and the average number of wet-pavement crashes per MVMT were computed for IRI < 1.5 m/km (95 in./mi), 1.5 to 2.7 m/km (95 to 170 in./mi) and > 2.7 m/km (170 in./mi). Results obtained from normalizing (by distance and MVMT) for each corridor are summarized in Table 2.

The average number of all crashes per section and the average number of wet-pavement crashes per section were observed to increase as pavement condition worsens (lowest for “good” and highest for “unacceptable” pavement condition categories) when analyzed using data for I-40 in Durham County (tinned concrete pavement). When analyzed based on MVMT for the same corridor, the number of all crashes per MVMT was observed to be lowest for “unacceptable” pavement condition followed by “good” pavement condition. On the other hand, the number of wet-pavement crashes per MVMT is lowest for “good” pavement condition while it is fairly equal for “acceptable” and “unacceptable” pavement conditions. The values of each measure for “good” pavement condition category are less than averages computed without accounting for IRI.

When analyzed using data for I-40 in Pender County (asphalt pavement), the average number of all crashes per section and the average number of wet-pavement crashes per section was lowest for “good” pavement condition category. A similar finding was observed when analyzed based on MVMT for the same corridor. The values of each measure for “good” pavement condition category are also less than averages computed without accounting for IRI for this corridor as well. No sections were observed with “unacceptable” pavement condition.

Overall, providing “good” pavement condition seems to be suitable even from a safety perspective along I-40 in Durham County (tinned concrete pavement) and I-40 in Pender County (asphalt pavement). Therefore, providing “good” pavement condition or low IRI value would not only result in improving fuel efficiency and reducing emissions on all pavement types but it also enhances safety.

From scatter plots based on all crashes, it can be seen that more sections with “good” pavement condition had the highest number of all crashes (indirectly indicating that a low IRI may result in more all crashes per section). While the IRI values and ranges seem to be overall comparable, providing lower IRI values seem to encourage motorists to speed affecting their braking performance under normal weather conditions along such sections.

<table>
<thead>
<tr>
<th>Corridor</th>
<th>Measure</th>
<th>IRI</th>
<th></th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.5 m/km (&lt; 95 in./mi)</td>
<td>1.5 to 2.7 m/km (95 to 170 in./mi)</td>
<td>&gt; 2.7 m/km (170 in./mi)</td>
</tr>
<tr>
<td>Pavement condition category</td>
<td>Good</td>
<td>Acceptable</td>
<td>Unacceptable</td>
<td>Good</td>
</tr>
<tr>
<td>Durham County I-40 (Tinned Concrete)</td>
<td>Average # of all crashes per section</td>
<td>1.33</td>
<td>1.57</td>
<td>1.67</td>
</tr>
<tr>
<td></td>
<td>Average # of wet crashes per section</td>
<td>0.11</td>
<td>0.25</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Average # of all crashes per MVMT</td>
<td>1.26</td>
<td>1.39</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>Average # of wet crashes per MVMT</td>
<td>0.10</td>
<td>0.21</td>
<td>0.20</td>
</tr>
<tr>
<td>Pender County I-40 (Asphalt)</td>
<td>Average # of all crashes per section</td>
<td>0.65</td>
<td>0.71</td>
<td>No observations</td>
</tr>
<tr>
<td></td>
<td>Average # of wet crashes per section</td>
<td>0.09</td>
<td>0.10</td>
<td>No observations</td>
</tr>
<tr>
<td></td>
<td>Average # of all crashes per MVMT</td>
<td>3.03</td>
<td>3.35</td>
<td>3.07</td>
</tr>
<tr>
<td></td>
<td>Average # of wet crashes per MVMT</td>
<td>0.40</td>
<td>0.47</td>
<td>0.41</td>
</tr>
</tbody>
</table>

6. Summary and Conclusions

This paper presents preliminary results towards thresholds for pavement condition maintenance by examining the relationship between IRI and crashes and comparing them with fuel efficiency perspective. Data for two study
corridors, first one with concrete pavement and the second one with asphalt pavement, were gathered, processed, and analyzed to perform research and identify the thresholds.

Profile elevation data collected using a laser profilometer and analyzed using ProVAL 2.7 software indicate that IRI is less than 2.7 m/km (170 in./mi) and ride quality is either “good” or “acceptable” for ~99% of sections considered in this research. It can be concluded from the scatter plots generated using IRI and crashes that risk to travelers in terms of crashes per section increases with an increase in IRI value. Findings from this research complement general findings from other researchers that targeting and maintaining IRI less than 1.5 m/km (95 in./mi) will lower risk to motorists under adverse weather conditions. Some differences were observed when analyzing using all crashes. The overall findings seem to be fairly consistent irrespective of the pavement type.

Crashes could happen due to driver error, vehicle failure, or poorly designed geometric condition in addition to poor pavement condition. Information pertaining to pavement condition was not explicitly available in the crash database for this research. Incorporating this factor and considering only crashes caused by poor pavement condition may yield accurate results and provide more meaningful insights.

The proportioning of the aggregate and mortar mix or surface-finishing techniques influence pavement roughness and IRI. Likewise, years since built or re-paved will also have an effect on IRI. Both study corridors considered in this research are Interstates with fairly similar design characteristics. However, the characteristics will vary for lower functional roads. The role of these characteristics (by considering corridors of different functional classes), pavements with different mix and finishing techniques, and years since built or re-paved on safety and in defining thresholds warrant further investigation.

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