Freeway crashes in wet weather: the comparative influence of porous and conventional asphalt surfacing

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Abstract

This paper analyses the correlation between the number of crashes on freeways and weather conditions on dense and porous asphalt before and after road modernization operations. The data were collected along 43 km of the A3 freeway, located in Southern Italy from the Tarsia road interchange to the South Cosenza interchange. Crash data were made available by the Police Station of North Cosenza, with traffic data from the ANAS Compartment in Cosenza, and the rainfall measurements were provided by the ARPACAL Centre in Calabria. Data were collected over two periods: before the modernization operations with existing dense asphalt and after modernization using porous asphalt. A porous pavement system is a structural and environmentally mindful alternative to the traditional pavement system. Safety tests were carried out correlating the number of crashes to the rainfall detected using two rain gauges and the traffic data. The results show that crash frequency depends considerably on the intensity of rainfall, both for porous and dense asphalt. In the first case, the accident rate increases to a rainfall of 0.5 mm/h, and then decreases due to probable greater prudence adopted by drivers in adverse meteorological events. The use of porous asphalt allows a reduction in the accident rate both in adverse meteorological conditions and for light rain, and confirms that, in terms of risk, the psychological effect on drivers increases with the amount of rain on the road rather than a reduction of adherence on a wet road surface.

1. Introduction

Much research has shown that crashes are often due to bad decisions by drivers made in environments created by engineers (Dell’Acqua, 2011). International research (Esposito et al., 2011) has thus suggested a variety of approaches to analyze the road traffic safety level on the basis of an assessment of accident rates and frequency.
Road traffic safety has since become a worldwide priority and one of the major factors for a description of the state of the traffic system in terms of both positive or negative changes (De Luca et al., 2011).

The rapid removal of storm water discharged on the roadway is indispensable for the safety of drivers, particularly when high intensity rainfall events raise the risk of total loss of adherence between tire and road (aquaplaning). To do this, the Italian Standard requires a minimum cross-slope of 2.5% except for the road areas where horizontal curvature changes exist.

An effective contrast to the development of excessive water veils is offered by porous asphalt (Barrett and Shaw, 2007): this is a superficial layer of asphalt pavement with high porosity power (over 20%). Barrett and Shaw (2007) showed that a porous asphalt overlay, also known as a permeable friction course (PFC) or open graded friction course (OGFC), is a layer of porous asphalt approximately 50 mm thick which is often applied on top of conventional asphalt highways to enhance safety and reduce noise. The quality of storm water runoff from a four-lane divided highway in the Austin, Texas area was monitored before and after the installation of a PFC. This research also analyzed runoff produced during discreet storm events over a 21-month sampling period. Observed concentrations of total suspended solids and pollutants associated with particulate material were much lower in the runoff from the PFC than those of the conventional asphalt surface. Concentration reductions were observed for total suspended solids (92%), total lead (91%), total copper (47%), and total zinc (75%). From these results it is evident that the runoff generated by the PFC surface is of better quality than that from the traditional asphalt surface.

A porous pavement makes it possible to incorporate a high flow of rain and, subsequently, to canalize it along the edge to filter it. Tan et al. (2004) explained in their research how the drainage performance of a porous asphalt surface depends on the drainage properties of the asphalt mixture as well as the geometric design of the individual road sections. The test apparatus consisted of a rectangular wooden test mold with a rectangular opening on the top, which was fitted to a rectangular water inlet. The aim of the experimental setup was to measure the time taken to fill the pail at each end under a constant head of 100 mm of water in the rectangular water inlet located at the top center of the mold. All test specimens were rectangular blocks; using different sections of each specimen, both the horizontal and vertical one-dimensional flow coefficients of permeability were found experimentally using laboratory parameters. With the inclusion of cross slopes in the pavement, the increase in drainage capacity of the porous asphalt surface reaches these values: 37.7% for pavement with 0% cross slope, 126.3% for pavement with 1% cross slope, 77.3% to 234.4% for pavement with 2% cross slope, 117.0% to 335.9% for pavement with 3% cross slope, 155.7% to 432.1% for pavement with 4% cross slope.

From the findings of the finite element analyses, a series of drainage design charts was developed for porous asphalt surface drainage courses. The porous asphalt technology is ideal for surfaces of roads exposed to large amounts of rainfall throughout the year. The high permeability of the mix guarantees fast drainage of the water away from the surface and thus increases road safety. However, the large amounts of water that flow through the asphalt have a negative effect on the material characteristics of the mastic and cause deboning of the aggregates from the mastic, called raveling (Kringos and Scarpas, 2005). To understand and quantify the physical processes and the mechanics leading to raveling, an extensive experimental and analytical investigation was undertaken by Kringos and Scarpas (2005) at Delft University of Technology in the Netherlands. One goal of the investigation was the development of the finite element tool RoAM (raveling of asphalt mixes), which is capable of simulating the gradual development of damage throughout asphalt mixes due to water infiltration. From the computational analyses it was concluded that simulation of water damage in asphaltic mixes is possible if the desorption characteristics as well as the diffusion and dispersion coefficients can be determined.

Experimental analyses on several porous concrete pavement mix designs and the use of admixtures were also developed. McCain and Dewoolkar (2010), for example, studied the strength and hydraulic conductivity of porous concrete mix designs for pavements. The experiments included compressive strength tests and falling head permeability tests on porous concrete specimens, using constituents readily available in Vermont. Effects of water-cement ratio and admixtures were examined. Multiple specimens were tested for a particular size. Admixtures such as a high-range water reducer and viscosity-modifying admixture had insignificant effects on
the compressive strength, hydraulic conductivity, and workability of the porous concrete mixes examined. Field cores displayed a much greater variability in hydraulic conductivity as compared to laboratory prepared specimens, largely because of the differences in compaction effort that are inherent to porous concrete placement in the field.

Dupont and Tourenq (1998) have carried out experimental analyses in France for several years to clarify the influence of different types of aggregates on asphalt-road surface adherence. This research aimed specifically to assess the different strength and resistance of stones in the mixture to reach desired roughness.

Harwood et al. (1988) investigated the impacts of wet pavement exposure estimation, including the conditions under which pavement wetness reduced surface friction and the time required for pavements to dry after rainfall. The authors noted that the difference between frozen and non-frozen precipitation was important in exposure measurement, because crashes recorded on forms classified road surface conditions by differentiating between the two.

Andrey and Yagar (1993) focused on empirical evidence of accident risk during and following rain events in Calgary and Edmonton, Canada. Their work included an examination of road wetness during rain events, finding that in the study area, pavements remained wet in excess of 1 h after a rain event. The researchers found that accident rates increased by 70% when rain was falling, but returned to normal levels as soon as the event came to an end.

Eisenberg (2004) investigated the relationship between precipitation and crashes in the United States between 1975 and 2000. The results indicated a negative and significant relationship between monthly precipitation and monthly fatal crashes. However, at the daily level of analysis, a strong positive relationship was estimated, similar to the findings of other studies.

Qiu and Nixon (2008) examined the interaction of weather and traffic safety performed between 1967 and 2005. Achieved results generally indicated that crash rates usually increase during precipitation, with snow having a greater effect than rain. It was found that snow increases crash rates by 84% and injury rates by 75% indicating, consequently, that snow depth had a negative impact on fatal crash rates.

Veneziano et al. (2009) illustrated in their paper how the Department of Transportation (Caltrans) developed a list of high-collision concentration locations that required further evaluation and treatment. One version of this list, Wet Table C, analyzes only wet accidents (those during or following precipitation). In developing Wet Table C, wet percent factors—which quantify the proportion of time per year during which pavement is damp enough to cause traffic accidents (measured on an hourly basis)—are used. These factors were originally developed at county level (i.e., one factor per county). Recent updating of factors allowed for their development at a finer spatial level (quarter-mile segments of roadway). The Mc Nemar test indicated that there was no statistical difference between lists produced using a singular wet percent factor and ones produced using finer resolution factors.

Many researchers have verified that one of the parameters that most influence safe driving is the speed variable (Török, 2011) and in the scientific literature some research works have dealt with speed prediction models to analyze real driver behavior (Dell’Acqua and Russo, 2010; Dell’Acqua and Russo, 2011 a).

The experimental analysis presented here is only one component of a larger study which has been under way on a number of roads for several years now with a view to improving performance, road management and safety (Dell’Acqua and Russo 2011 b, Dell’Acqua et al., 2011 a-b-c). This experimental study refers to a specified segment length of the A3 freeway located in Southern Italy: a relationship between the frequency of crashes in different weather conditions and two different types of surface asphalt were performed. The study confirms the benefit of porous asphalt use for drivers’ safety, and also extends this important function to events with low intensity: the elimination of the water film, even in non-hostile meteoric conditions, increases the real perception of tire adherence on the road surface.

The care and attention of drivers and the adoption of more conservative and safer behavior increases with rain intensity. It is believed that this is mainly due to the reduction of visibility through the windshield. Billotet et al. (2009) dealt with the analysis of the impact of rain on driver behavior and traffic operations. First, a generic methodology for assessing the effect of weather on traffic was proposed applying a multilevel approach: from
individual traffic data, the rain impact is assessed at microscopic level (time headways, spacing). Next, the same
data were used to extend the study to mesoscopic and macroscopic level. The mesoscopic level deals with the
effects of rain on platoons, and the macroscopic level resides in the analysis of the impact of rain on the
fundamental diagram enabling weather-responsive macroscopic traffic simulation. Second, following this
approach, an empirical study is carried out from individual data collected on a French interurban freeway.

2. Data Collection

The segment analyzed (see fig.1) belongs to the A3 freeway between Salerno and Reggio Calabria: it is
situated between 221 + 000 km, near the Tarsia interchange and 264 + 000 km near the Cosenza interchange.
This road segment is located on a flat area with a vertical grade of less than 3%.

Motorway A3 Napoli-Reggio Calabria is a freeway in the south of Italy, which runs from Napoli to Reggio
Calabria via Salerno. It runs through 3 regions: Campania (171 km), Basilicata (30 km), and Calabria (293.9 km).
Due to its notoriously poor conditions of maintenance, and its difficult route, the motorway has often been
taken as a symbol of the backwardness and the economic problems of southern Italy.

Since the early years of the twenty-first century this segment has been subject to road modernization
operations which, apart from localized adjustments, aimed to bring roadway width into conformity with the
Italian Standards published in the first decade of the century and the use of porous asphalt despite the high cost of
installation and maintenance activities. The amount of porous road paving reflects the real traffic volume with an
ADT of 12,000 vehicles per day with peaks of 16,000 vehicles per day on the road segment in the Montalto -
South Cosenza direction. This is the result of the overlapping of long-distance traffic flows from north to south
with the local traffic of the Cosenza Province. There was also an annual increase of 2.5% according to National
data. Data collection covered the following time intervals:
• the period before road modernization operations from 1 November 1998 to May 31, 1999
• the period after road modernization operations from 1 November 2003 to May 31, 2004

The microclimate features of the analyzed area were obtained from the Regional Database for the Protection of the Environment located in Cosenza (ARPACAL) that made the weather conditions for this site available in terms of rainfall using two rain gauges: the first is located in Torano Scalo and shows the weather conditions between 221 + 000 km and 243 + 500 km, and the second is situated in MontaltoUffugo and shows the weather conditions between 243 + 500 km and 264 + 000 km.

Traffic data for vehicles per day were constantly recorded for the whole day. They were made available by the Cosenza ANAS, which collects continuously from a station located near the analyzed segment.

The number of crashes was made available by the police in charge of the road network of North Cosenza and the Cosenza SOS service. The reports analyzed contain the following information:

• a description of the mileage and geometric features of the road where the crash happened (i.e. tangent, circular element, etc)
• date and time
• weather conditions (i.e. sunny, rain, snow, etc.)
• surface conditions (i.e. dry, wet, icy, etc.)
• number of vehicles involved
• consequences (i.e. only material damage, number of injuries, number of deaths)
• type (i.e. rear-end collision, side impact, frontal-impact side, heel, etc.)

For each crash event, a mean rainfall value was attributed using the information made available by the archives of the multi-functional risk ARPACAL in Calabria which records the rainfall on an hourly basis. The database was built up according to the following stages:

• the rainfall within a range of between 0.2mm/h to 2.00 mm/h was divided into 10 classes of 0.2 mm/h each
• each class was characterized by its frequency equal to the ratio between the number of rain hours with values within the limits of the specified class and the total number of hours that the experiment lasted
• the traffic data for each hour of rain were associated with the corresponding classification of rain hours where the rain hour falls, and then the distribution of traffic flows according to the classes of rainfall conditions was analyzed
• similarly, the number of crashes occurring at particular times when it was raining were associated with the class of relative intensity and an analysis was carried out to verify the existence of a correlation between crashes and the corresponding classes of rainfall intensity

3. Data Analysis

To compare the safety conditions of the different scenarios where the crashes happened two synthetic indices were produced: \( I_1 \) and \( I_2 \). Equation 1 shows the \( I_1 \) index:

\[
I_1 = \frac{10^8 * N}{365 * L * K_1 * 24}
\]

where
N is the number of crashes during the experiment
• L is the total length of the segment analyzed, which is 43.00 km
• K1 is the ratio between the total number of vehicles passing for each observed rain intensity class and the total hours of rain during the observation period; this value represents the average traffic corresponding to the observed rain class for the whole of the period being studied.

In equation 1 the information is related to the year through the multiplier $365 \times 24$, and the unit of traffic flow was assumed to be $10^8$ N to obtain immediate interpretations of the results, since crashes are few and are a rare event in relation to the traffic. In conclusion, the $I_1$ index is a measure of the relationship between the number of crashes during the experiment and the corresponding traffic transiting in the same rainy conditions for the road segment analyzed. Equation 2 shows the $I_2$ index:

$$I_2 = \frac{10^8 \times N \times S_v}{365 \times L \times K_1 \times 24}$$

$I_2$ index differs from the previous one only in the introduction of the severity of accidents factor $S_v$, which takes into account the personal injuries (number of injuries and/or deaths) caused by the crash; the severity of accidents factor was arbitrarily assigned (Table 1).

Table 1. Crash severity

<table>
<thead>
<tr>
<th>Crash Consequences</th>
<th>$S_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No injuries</td>
<td>1.0</td>
</tr>
<tr>
<td>from 1 to 3 injuries</td>
<td>1.5</td>
</tr>
<tr>
<td>from 4 to 8 injuries</td>
<td>2.0</td>
</tr>
<tr>
<td>more than 8 injuries</td>
<td>2.5</td>
</tr>
<tr>
<td>at least 1 dead</td>
<td>3.0</td>
</tr>
</tbody>
</table>

3.1. Dense Asphalt

Applying the described methodology to collected data concerning the period before the road modernization operations gives the profiles of $I_1$ and $I_2$, respectively, on the basis of rain intensity classification (figure 2).
It can immediately be deduced from these two diagrams, that for two indices the trend initially increases with the intensity of rain up to 0.4 mm/h, above which the probability of a continuous film of water is high.

The experiment results support this expectation: drivers in the rain continue to maintain behavior comparable to that of drivers on the dry road until there is a continuous film of water on the surface road.

This is a negative aspect for driver safety because drivers fail to understand the reduction of tire adherence on the road surface.

Psychological attitude emerges in terms of increased attention when driving and speed reduction changes only when the driver detects the presence of the continuous veil of water.

For the most noticeable events, the crash rate tends to decrease as the intensity of the rain increases.

### 3.2. Porous Asphalt

The procedure adopted for data collected on dense asphalt was applied to data collected after the modernization operations, as shown in figure 3 that illustrate the diagrams of the $I_1$ and $I_2$ indices on the basis of the rain intensity class on porous asphalt.

In the case of porous asphalt, the $I_1$ and $I_2$ indices decrease consistently with increasing rain intensity in the same way as dense asphalt (Figure 3) where same low values of the indices correspond to the small number of crashes recorded: this increased driver safety is due to the absence of water film that causes indifference on the part of drivers to the weather conditions and, subsequently, to the existing tire adherence on the road surface.

![Fig.3. Porous asphalt: I1 and I2](image)

#### 3.3. Dense Asphalt versus Porous Asphalt

Analyzing the collected data and the results, (global and unbundled) it is immediately clear that there is a substantial advantage in the use of porous asphalt for driver safety, in terms of crash frequency, severity and consequences: the total number of injurious crashes in the rain for the analyzed road segment decreases (see Fig.4).
The models (3) and (4) provide a summary of the results of the experimental analysis, using synthetic indices according equations (1) and (2), for two analyzed surface conditions: dense ($I_{DA}$, $I_{PA}$) and porous asphalt ($I_{2DA}$, $I_{2PA}$).

\[
I_{1DA} = -13.48 \cdot R_i + 25.66 \quad \rho^2 = 0.719 \\
I_{1PA} = -2.625 \cdot R_i + 4.77 \quad \rho^2 = 0.509 \\
R_i > 0.40[mm/h]
\]

\[
I_{2DA} = -15.11 \cdot R_i + 29.71 \quad \rho^2 = 0.727 \\
I_{2PA} = -2.72 \cdot R_i + 4.94 \quad \rho^2 = 0.603 \\
R_i > 0.40[mm/h]
\]

where $R_i$ is the rain intensity.

In addition, the presence of porous asphalt (Fig. 5) intensity highlights the effectiveness of the risk message transmitted to the drivers when hostile meteorological events develop, increasing in any case the safety conditions of drivers and improving their driver behaviour also in good weather conditions.
4. Conclusions

A porous pavement is an environmentally conscious alternative to a traditional asphalt or concrete pavement system. Porous pavement has, in addition to the environmental benefits, also structural and economic advantages. It creates a drier surface during a storm event making these systems safer for drivers, produces less noise than traditional systems, and a porous pavement could negate the need for other forms of storm water treatment, such as retention ponds that can be both costly and impractical in many situations.

In this paper we have illustrated different safety conditions for drivers moving on a freeway located in southern Italy.

The road segment was studied before and after modernization operations, where the main action was the use of porous asphalt to replace existing dense asphalt; a relationship between the frequency of crashes in different weather conditions and the two different types of surface asphalt was analyzed.

The analyzed porous asphalt pavement was seven years old; the circumstances have proved, despite little maintenance over the years, the effectiveness of the surface drainage thanks to the macrotexture presence which facilitated the expulsion of water by the wayside.

There was also an increase in safety due to the drivers’ behavior with the elimination of the water film, even in non-adverse meteoric conditions, increasing the real perception of tire adherence on the road surface.

The attention of drivers and the adoption of more conservative and safer behavior increases with the intensity of rain. It is believed that this is mainly due to the reduction of visibility through the windshield.

References


