Design, construction, and in-service causes of premature pavement deterioration: a fuzzy Delphi application

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Abstract

Flexible pavements are prone to premature deterioration, and researchers are unresolved regarding the importance of the underlying causes resulting in inappropriately selected modelling parameters and increased uncertainty in predicting subsequent behaviour and performance. A windshield survey, literature survey, and fuzzy Delphi study are undertaken as complementary approaches to costly conventional investigations to identify reasons for flexible pavement deterioration in the design, construction and lifespan phases. Overall, the results revealed that the lifespan phase consists of the most contributors to pavement deterioration, which is approximately twice as much as the design and construction phases. However, the findings suggest that most causes of deterioration in the lifespan phase can be attributed to deficiencies in the preceding phases. Experts believe that structural and traffic are the most significant contributors to pavement deterioration, more so than construction, environment and maintenance factors. Additionally, the surface and subgrade layers were deemed to be the most problematic. Applying the Fuzzy Delphi method minimises the ambiguities associated with the causes of pavement deterioration identified in the literature and is advantageous for limited data. This study proposes measures for improving the design and construction of more sustainable tropical pavements. Improved knowledge of the causes of deterioration is vital for selecting the appropriate design, construction, and maintenance strategies.

Keywords: Asphalt pavement; deterioration; distress; design; construction; lifecycle; fuzzy Delphi

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Introduction

The deterioration of hot mixed asphalt (HMA) pavements is inevitable (Garber and Hoel 2009) and has been problematic for years. Signs of deterioration are usually visible on the pavement surface layer and manifest as distress –distortion, disintegration and fracture (Attoh-Okine and Adarkwa 2013). Pavement deterioration causes unnecessary delays in traffic flow, road traffic accidents and the consequent loss of life and property damage (Eijnde 2015; Ogundipe 2008; Rashid and Gupta 2017; Tarawneh and Sarireh 2013). Apart from being aesthetically unpleasing, damaged flexible pavements continue to be unsustainable because of their premature deterioration—unfortunately, forthcoming solutions on factors affecting defect occurrence and a consensus on explanations for conditions leading to their manifestation are limited throughout the project lifecycle. Evidently, the myriad of factors proposed for modelling pavement behaviour and performance predictions and for explaining deterioration varies among authors. See, for example, the factors to explain rutting proposed by Xu and Huang (2012), Gao et al. (2009), Walker (2009), Huang et al. (2009), Ling et al. (2020), and Sybilski et al. (2013). Such variance exists because it is difficult to determine which pavement layer contributes the most to surface deformations (Walker 2009). After all, faults are interconnected, and focusing on one problem without considering others occurring throughout the pavement life cycle restricts interpretation (Chilukwa and Lungu 2019).

Previous studies have identified flexible pavement deteriorating conditions using windshield surveys (Alaamri et al. 2017; Scholz and Rajendran 2009; Zumrawi 2015); visual inspection (Al-Arkawazi 2017; Alaamri et al. 2017; Chen et al. 2003; Rashid and Gupta 2017), condition surveys (Scholz and Rajendran 2009; Stallings 2016); and secondary methods (Afolayan and Abidoye 2017; Farouq et al. 2017). In these investigations, the causes of distress were determined through literature reviews (Afolayan and Abidoye 2017; Kumar and Gupta 2010; Rashid and Gupta 2017); forensic investigations (Chen et al. 2003; Zumrawi 2015); questionnaire surveys (Farouq et al. 2017; Ibraheem and Gani 2014); observations/opinions (Adlinge and Gupta 2013; Okigbo 2012); and miscellaneous methods (Rather and Lateef 2016; Tarawneh and Sarireh 2013). These approaches acknowledge in principle that several factors are responsible for pavement deterioration and that no solitary method is confirmatory, as deterioration is a complex and sometimes unpredictable phenomenon. The resulting lack of consensus on the causes of pavement deterioration has led to neglect (Al-Arkawazi 2017; Rashid and Gupta 2017; Wada 2016), omission, and poorly described data collection approaches (Acimovic et al. 2007; Adlinge and Gupta 2013; Imran et al. 2015; Wada 2016).

The methodologies employed to identify distress causes were further constrained by incompleteness, close-endedness of questionnaires, and a lack of data triangulation. Some of the reported reasons for degradation are vague and wide in scope, such as inadequate drainage and poor construction. Other variables, such as poor road alignment and geometric design, are redundant (Tarawneh and Sarireh 2013). Also, there is sparse mention of climate change as a critical factor, despite it being an urgent eminent challenge (UN 2016) and is likely to have accelerated effects on deterioration. It is unclear which lifecycle phase causes the most deterioration or where some factors are most pronounced. The reasons for these misconceptions may be a lack of knowledge, literature, techniques, popularity, or misguided interpretation. This study addresses these issues for additional reflections and critical analysis by updating the pavement deterioration literature using an empirical method. Providing an improved understanding of pavement deterioration is needed to make accurate judgements of its weakening behaviour (Eijnde 2015), that is, to correctly identify the signs of deterioration and their causes.

The types, severity, and reasons for pavement distress varies; hence, researchers and organisations have offered regional or country-specific guidelines (Llopis-Castelló et al. 2020). The intent of which is to provide objective criteria for assessing pavement quality, defining management strategies, and providing guidance on deterioration factors. Such provisions facilitate model development that advances state of the art, which relies on the use of AI to diagnose failures (Alzraiee et al. 2021; Praticò et al. 2020). However, AI systems are limited because of the complex and dynamic environmental circumstances. For example, diagnosing cracks while water is on the road surface may be inaccurate when using these systems (Cao et al. 2020). Detecting faults requires human intervention; therefore, real-time performance is currently unfeasible. Consequently, manual pavement surveys are often employed to discover, categorise, and measure pavement defects (Ouma and Hahn 2017). The lack of data from expensive preparations, including non-destructive and destructive testing, exacerbates this dependency (Johnson et al. 2017). Moreover, Llopis-Castelló et al. (2020) claimed that financial restrictions and a lack of historical data make assessing pavement deterioration problematic.

The performance assessment of pavements is unpredictable owing to the substantial variability associated with pavement life and traffic repetitions. Uncertainty exists in traffic estimation, variability in material parameters and various assumptions, approximations and empiricisms involved in the analysis and design process. The complexity of pavement construction, material behaviour, traffic characteristics, and quality control variables necessitates consideration of such uncertainties (Kalita and Rajbongshi 2015). The impetuous goal is to encourage consideration of a comprehensive set of factors which provide an understanding to quantify the typical variability associated with pavement throughout its life cycle (Stubstad, Tayabji, & Lukanen (2002). Fortunately, existing non-destructive approaches already recognise this uncertainty as the imprecise language used to describe pavement conditions demonstrates this. For example, the terms "poor," "very bad," "good," and "outstanding" are often used to describe pavement conditions are subjectively uncertain. Fuzzy sets adequately describe this range (Elton and Jung 1988) as fuzzy numbers can effectively categorise pavement degradation, as it accounts for the uncertainty associated with evaluating engineering parameters (Bui et al. 2020; Elton and Jung 1988). Thus, experts' subjective views can describe objective measures within acceptable statistical means (Martin et al. 2017).

Pavement degradation varies due to differences in economies, climatic conditions, geology, design, construction, and maintenance practices. Despite several studies on tropical pavement deterioration, this problem persists, prompting the need to explain the most important design, construction, and lifespan factors affecting its deterioration and in-service quality. A windshield survey and visual inspection of flexible pavement distress along the highways in Trinidad were conducted. The identified causes of distress were determined from a literature review and then presented to experts involved in the design, construction, and lifespan phases to obtain a consensus on inclusivity and ranking using the fuzzy-Delphi approach. The proposed approach minimises professional judgement uncertainty. Ambiguity regarding the underlying reasons for the early degradation of flexible pavements leads to incorrectly chosen modelling parameters and increased uncertainty in projecting future behaviour. Understanding pavement disintegration is critical for optimising maintenance expenditures, addressing underlying causes, improving design and construction quality (Fwa 2006; Rashid and Gupta 2017; Schlotjes et al. 2011), and, more importantly, extending the useful life of pavements. This study confirms that expert judgement is useful in understanding pavement deteriorations and in guiding deterioration interventions.

Methodology

Figure 1 shows an overview of the research methodology applied in this study.

Field Survey

The Churchill-Roosevelt (CRH) and Beetham highways in Trinidad were used as case studies to identify the distress types. While these highways were constructed a decade apart, they were chosen because they are most similar in composition and function, and one exists as a continuation of the other. They commonly have six lanes, signalised intersections, and a similar traffic volume and load intensity. These highways connect Port of Spain (the Capital City of Trinidad and Tobago) and Arima (the second largest borough). Both the eastbound and westbound directions of the highways were surveyed. As shown in Figure 2, the road under inspection extends from the west at the beginning of the Beetham Highway (land marked by the South Quay Lighthouse) (A) and ends in the east at the Mausica Road/ Churchill Roosevelt Highway (CRH) intersection (J), where the six lanes of traffic end on the CRH. The length of the pavement under scrutiny was divided into nine sections for observation and recording of distress. The highways' major entrance and exit points were chosen as the beginning and ending points, respectively, to ensure that each section was subjected to a common traffic volume and intensity. Work by Attoh-Okine and Adarkwa (2013) was adopted for the windshield surveys to identify the distresses present on the highways. Instead of a walking survey, a windshield survey was selected for this study because of the highway's proximity to high-crime neighbourhoods, and safety was the decisive consideration (Miller and Bellinger 2014). The degree of distress along a particular section of the highway was observed. However, the density or precise distress locations limit the findings' interpretation. In this survey, an observer (a civil engineer) was seated in the passenger seat of a car moving at approximately 30 km/hr. in the slowest lane of traffic as the car stopped, photographically documenting the distress and severity while standing along the pavement edge. The survey was conducted on a national holiday when the traffic volume was comparatively lower than that on a regular day, which facilitated the visibility of all pavement lanes. Subjectivity in distress identification and severity was reduced using the guidelines provided by ASTM International (2018), Miller and Bellinger (2014), NAASRA (1987), and the Federal Highway Administration (2009).

Fuzzy Delphi Method (FDM)

The Delphi method is a decision support tool to assess group thinking by taking each expert's opinion individually and anonymously and subsequently merging them into one group opinion (Adler and Ziglio 1996; Habibi et al. 2015). It is recommended for situations where data are insufficient or when models for statistical prediction or judgment are non-existent (Gupta and Clarke 1996). Ishikawa proposed the fuzzy-Delphi approach (Hsu et al. 2010), which changes the standard Delphi method by accounting for expert judgement uncertainty (McKenna 1994), improving convergence, and decreasing high execution costs (Ma et al. 2011). Including fuzzy settings decreases inaccuracies because they are more linguistically ambiguous, as humans cannot resist vagueness, the antithesis of exactness (Novák and Dvorák 2011). The Fuzzy-Delphi method provides a more current scientific or technical information interchange than a literature study or the conventional Delphi (Delbecq et al. 1975). Fuzzy-Delphi has been used to determine road safety performance indicators (Ma et al. 2011), sustainable solid waste management barriers (Bui et al. 2020), and assess service industry mobility performance indicators (Kuo and Chen 2008), thereby, justifying its use in determining pavement deterioration factors.

Expert identification and panel composition

There are no exact criteria listed in the literature concerning Delphi expert selection (Hsu and Sandford 2007). The researcher's responsibility is to choose the most appropriate experts and defend that choice (Sumsion 1998). This study adopted the following requirements for 'expertise' as defined by Adler and Ziglio (1996):

i. knowledge and experience with the issue under investigation;
ii. capacity and willingness of the experts to participate;
iii. sufficient time to participate; and
iv. effective communication skills

It is important to have appropriate distinctions among expert groups to have significant conclusions; using heterogeneous groups may result in either no mutual agreement or meaningless aggregated results (Kuo and Chen 2008). For this reason, three homogenous panels of experts were engaged based on their involvement in different road lifecycle phases: design, construction, and lifespan. See Table 1. Ten design, thirteen construction, and thirteen lifespan experts participated in Tier 1 of the survey. However, only nine, seven, and eight design, construction and lifespan experts, respectively, responded to Tier 2. These 'dropout' rates were not expected to affect the study outcome because the panel sizes were satisfactory. According to Cantrill et al. (1996) and Mullen (2003), the panel size has no strict rules. Linstone (1978) added that a suitable minimum panel size is seven, but panel sizes range from 4 to 3000. Therefore, the panel size decision is empirical and pragmatic, considering factors such as time and expense. Usually, the time required to administer a Delphi survey is two weeks (Delbecq et al. 1975). In this study, time was not considered an influencing factor in dropout rates because the respondents were provided adequate time (three weeks) for each round. Reasons for participants' dropout included the change of work organisation and the inability to access the survey due to remote fieldwork location.

Brainstorming – factor determination

The literature review identified and summarised the existing research relating to HMA flexible pavement distresses and their contributing deterioration factors. An initial list was created to define the abstraction level at which participants added missing factors (Schmidt et al. 2001). Pavement deterioration can be approached from a very detailed or a much more generic viewpoint. The level of approach determines the eventual outcome and usability of the results. There was a search for a detailed level of deterioration factors in this study. The lists of factors obtained from the literature review were scanned thoroughly to ensure that duplicate, indistinguishable or inapplicable factors (e.g. ice, snow, and frost action) were not presented to the panellists as Trinidad is a tropical country. Examples of predefined factors were provided to guide the participants.

Questionnaire construction

Questionnaire 1 identified all relevant factors that generally contribute to pavement deterioration in the design, construction, and lifespan phases. Three separate questionnaires were created as the factors were considered per lifecycle phase rather than all together. Separate questionnaires were used for two reasons. First, using three different questionnaires prevented some participants from leaning toward one of the three phases. Creating three different homogenous groups yielded more reliable results, as participants answered questions within their field of expertise. According to Rowe et al. (1991), sensible questions are only sensible and pertinent to the panellist knowledge realm. Second, it would have been too intensive and demotivating if panellists had to rank all factors of the phases. Each of the three questionnaires contained two sections; section one sought to collect the participants' background information. Section two lists the general factors that originate during each lifecycle phase.

The experts were asked to appraise the list of factors by validating, deleting and adding missing deterioration factors from the initial lists derived from the literature review. In addition, to maximise the chance of defining all relevant factors, participants could submit as many suggestions as possible (Schmidt 1997). Their vagueness, phase of origin, or redundancy was considered for adding to or excluding the suggested factors from the list. Questionnaire 1 was created using Adobe Acrobat and was administered mainly online via email. Also, in some instances, the participants expressed a preference for physical copies. Feedback received from Section 2 for each questionnaire 1 (design, construction and lifespan) was analysed by adopting Alexandrov et al. (1996), Sinha et al. (2011), and Morris et al. (2014) criteria. The criterion for an agreement was that at least 67% of the respondents gave the same response. This criterion was used because these studies had similar 'nominal' (yes/no) scales as this study. With the condensed results gathered from Questionnaire 1, three subsequent Questionnaire 2 were presented to the experts. They were asked to use either Google Forms or Adobe Acrobat to rank the identified factors on a seven-point Likert scale. Google Forms was used in this round because some participants expressed issues using Adobe Acrobat online.

Identifying an appropriate spectrum for fuzzification of linguistic expressions

A triangular fuzzy membership function was established to fuzzify respondents' linguistic expressions taken from a set of acceptable values (no effect, little effect, … medium effect, … extreme effect). The linguistic variable was defined as the number of years of shortening the pavement lifespan. The rationale for using a scale with the linguistic variable "shortening in lifespan" was that it would be more intuitive for participants if they could express the severity of deterioration in years (Eijnde 2015). In addition, the shortening in lifespan provides a uniform measure across all defects and reduces the uncertainties associated with terminologies such as extremes, which may vary among different defects. Therefore, this study used a shortened lifespan as the term set T = {0 years, 0 to 1 years…4 to 5 years, >5 Years}. Choosing a Likert scale is advantageous and is a reliable data collection approach because it can access both observable and latent variables that are not directly observable, and the consequent results can be utilised for statistical inference (Li 2013).

Higher-order scales increase reliability but begin to plateau at 7 with no further increase beyond 11 (Finstad 2010). However, there are intense criticisms of increasing scale because of the difficulties in resolving the intensity of feelings, measurement errors, and confusion from too many choices, which induces laziness (Li 2013). Besides, the seven-point scale provided the best direct rating and was determined to be the most accurate and easy to use (Diefenbach et al. 1993). A seven-point scale was chosen because 0 to > 5 years can be evenly distributed over a seven-point scale while maintaining a range of 1 year. According to Eijnde (2015), discussions with experts confirm that a range of one year is the desired level of granularity, and there is no reason to go beyond '> 5' years as this is very exceptional to happen in real life. There is a corresponding triangular fuzzy number (TFN) for each year of life span shortening, as shown in Table 2. Each identified factor was ranked by requesting participants to select the most probable 'shortening in lifespan' effect on the pavement life. Hence, all experts' Likert scale responses for each factor were fuzzified. The first, second and third values are referred to as the 'minimum fuzzy value (a)', 'optimal fuzzy value (b)' and 'maximum fuzzy value (c)', respectively. The minimum value represents the minimum shortening in lifespan that can occur as a result of a factor. Similarly, the optimal (b) and maximum (c) values are the respective most probable and maximal shortening in lifespan due to a factor.

The consensus of Questionnaire 2

This study utilises triangulation statistics to determine the distance between expert panel members' levels of consensus. The feedback received from Questionnaire 2 was screened for consensus. A consensus was reached if at least 70% of the responses for each factor were within one standard deviation of the mean response (average fuzzy number) (Diamond et al. 2014; Hasson et al. 2000; Henderson and Rubin 2012; Slade et al. 2014; Vogel et al. 2019). The average fuzzy number ($TFN_{average}$) was determined for the minimum, optimum and maximum fuzzy values using equation (1).

$$TFN_{\ average} = \frac{\sum Fuzzy\ values}{Number\ of\ Experts} \qquad (1)$$

For each factor, the distance (d) between the respondents' TFN and the average TFN was determined, followed by the average distance ($\tilde{d}$). Next, the standard deviations (s) of the responses were calculated, followed by the lower ($\tilde{d} - \sigma$) and upper ($\tilde{d} - \sigma$) limits for acceptance. The distance (d) between the two triangulated fuzzy numbers m = (m_1, m_2, m_3) and n = (n_1, n_2, n_3), as expressed by Abdulkareem et al. (2020), is given by equation (2):

$$d(\tilde{m}, \tilde{n}) = \sqrt{\frac{1}{3}\left[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2\right]} \quad (2)$$

The standard deviation, s, is calculated using equation (3), where N = number of experts; x = distance between the average response and the respective expert's response; and μ = average distance for the factor.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \quad (3)$$

Aggregation of fuzzified values

For the factors of questionnaire two that achieved consensus, the group opinion of (i = n) experts for each factor (j) was aggregated using the geometric mean adopted from Hsu et al. (2010) and Chen (2014), see equation (4).

$$\tilde{w_j} = (a_j, b_j, c_j) \quad (4)$$

Where: $\tilde{w_j} = aggregated\ triangular\ fuzzy\ number$; $a_j = min\,\{a_{ij}\}$; $b_j = \frac{1}{n}\sum_{i=1}^{n} b_{ij}$; and c_j=max $\{c_{ij}\}$.

Defuzzification

Defuzzification is required because fuzzy numbers cannot be ranked because they are not crisp (precise) values. The graded mean integration representation method, proposed by Chen and Hsieh (1999) and described in equation (5), is used to aggregate the fuzzy triangular numbers for each factor in the process of defuzzification.

$$S_j(expert\ group\ opinion) = \frac{a_j + 4b_j + c_j}{6} \quad (5)$$

This defuzzification equation weighs the optimal value (*b*) four times that of the minimum (*a*) and maximum value (*c*). This weighting was appropriate because the most probable value was the most valuable for this study.

Selecting the threshold /screening criteria and ranking

A screening threshold was established to determine the significant deterioration factors. The threshold is typically 0.7, but it varies based on the researcher's opinion in different studies (Habibi, Jahantigh, and Sarafrazi 2015). In this study, the threshold value used to eliminate the least significant factors was one standard deviation below the mean. If the crisp value of the defuzzification of aggregated experts' opinions is larger than the threshold, the criterion is confirmed. If the criterion was less than the threshold value, the factor was removed. Finally, the factors were ranked from highest to lowest by ranking their crisp values (Sj).

Bias

According to Hallowell and Gambatese (2010), eight different types of bias may influence the outcome of a Delph study: Collective Unconscious, Contrast Effect, Neglect of Probability, Von Restorff Effect, Myside Bias, Recency Effect, Primacy Effect and Dominance. Collective unconsciousness arises when participants conform to popular trends selected by their peers without being objective. This bias was reduced by gathering the experts' responses online via 'Google Survey'. In cases where physical questionnaires were delivered, the participants were allowed to complete the questionnaires at their convenience. Contrast effect occurs when a given subject's perception is enhanced or diminished by the immediately preceding subject's value. Using the same scales for Questionnaire 1 and Questionnaire 2 items minimised this bias. The participants' ability to disregard the probability of certain occurrences is termed Neglect of Probability. This bias considers the scenario where individuals focus on the potential consequences of an outcome without examining the probability of its occurrence. This bias did not affect this study since the probability or frequency of the factors were not considered. The following biases were reduced by checking the consensus of the panellists for both rounds of the study: Von Restroff Effect - a person's recall of extreme events over lesser events; Myside – occurs when someone has a one-sided perspective of an issue; Recency Effect - an individual's recall of only recent events; and Primacy - participants placing unconscious importance on initial questions. Dominance arises when one group member exerts significant influence over the other members' evaluations: anonymity and equal weighing of answers control this frequent bias source.

Validation

The group thinking approach assured the validity of the deterioration causes derived from the fuzzy Delphi method (Skinner et al. 2015). According to the defined criteria, group consensus for the factors in each phase was determined at the end of both rounds of the study.

Results

Of the seventeen types of flexible pavement distresses identified from the literature, the windshield survey, which included visual inspection, found longitudinal cracking, fatigue cracking, rutting, polishing, and potholes most prevalent along the highway sections. Table 3 identifies the severity of the distress throughout the respective sections of the highway.

Table 4, Table 5, and Table 6 present the experts' fuzzified responses to the causes of pavement deterioration for the design, construction and lifespan phases. Table 7 shows the ranked causes of deterioration for each distress.

The ranked factors for the general causes of deterioration in the design, construction and lifespan phases are shown in Table 8. For each of the distresses identified in Table 3, the experts' ranked causes are presented in Table 9.

Causes of premature highway pavement deterioration

Three panels of experts with design, construction, and lifespan phases identified and ranked the causes of highway pavement deterioration. In their opinion, structure, traffic, construction, environment, and maintenance are the major categories contributing to premature highway pavement deterioration.

Structure

A pavement's structural soundness is critical to its performance throughout its lifespan, where most design inadequacies are manifested. The experts believe that pavements are structurally inadequate owing to insufficient design knowledge, faulty design parameters, and poor preliminary geological investigation. These factors are antecedent to other causes, which are related to pavement thickness and properties. Design and construction experts consider inadequate layer thicknesses a pivotal contributor to deterioration, as previously acknowledged by (Zhao and Al-Qadi 2016), as the most crucial factor for the majority of asphalt pavement design methods. In the general list of design factors, inadequate base and pavement layer thicknesses were ranked third and fifth, respectively. Similarly, a thin asphalt layer over bridges and roadways was identified as contributing to both meandering cracks and potholes. When the pavement thickness is insufficient, the subgrade applied stress is more significant than it can resist, resulting in deflection and premature pavement failure (MAPA 2014). The lifespan experts believed that such behaviour could account for structural failure/movement of the bottom layers and the resulting fatigue cracking, rutting and depressions. Hence, the experts deemed the subgrade one of the most problematic components.

Unstable/expansive subgrade soils were ranked as the primary cause of bumps, depressions, longitudinal, transverse, and block cracking. Similar observations were noted by (Uge 2017) in Ethiopia, where such soils experience more than usual differential settlement. Unstable/expansive subgrade soil is ranked as a general cause of deterioration and the primary reason for meandering cracking. Expansive soils are common along the case study route, often inflicting substantial pavement damage in the island's northern, central and southern regions (Ramana 1993; Venkatarama 2003). Therefore, the strength of the subgrade must be thoroughly evaluated before commencing the structural design of the pavement. Notably, poor preliminary geological investigation was ranked among the general causes of deterioration.

It is not surprising that inadequate pavement design for specific soil conditions was ranked as the leading cause of rutting, bumps, depressions, fatigue, and longitudinal and transverse cracking. For highways not affected by expansive soils, their unstable subgrade may be due to inadequately prepared subgrades, more specifically, inadequate compaction (ACI Asphalt & Concrete Inc. 2017; Clarke 2015; Powell 2018) or poor subsurface and surface drainage (Clarke 2015; Lavin 2003; Roadex Network 2014). Overall, the results suggest that inadequacies in the design and construction phases can be the root of this in-service problem.

The quality of pavement materials was also identified as a significant contributor to structural deterioration. The design and construction experts conveyed that the quality of the HMA mix and aggregates used for construction compromises the pavement's structural integrity. The lifespan experts affirm that the deterioration was largely due to the degradation of the pavement materials initially used.

Experts identified the bitumen mix's lack of stability in the design phase as the primary cause of corrugation and shoving, confirming Wada (2016) findings. The findings demonstrate that both defects are of a similar origin (Adlinge and Gupta 2013). In contrast, in the construction phase, poor binder to stone adhesion' was identified as the third most significant cause of raveling and the ninth general cause of deterioration. In addition, the low binder content in the HMA mix was ranked as the seventh general cause of deterioration. Inappropriate aggregates were ranked as the second most significant general cause of deterioration. Construction experts ranked it as the leading cause of rutting, bumps, shoving, and ravelling, affirming the influence of aggregates on these defects as unquestionable (Adlinge and Gupta 2013; Huang et al. 2009). The degradation of the pavement materials described as deterioration of aggregates and ageing of binder in the surface course was ranked as the third and fifth general cause of deterioration in the lifespan phase. The loss of adhesion in the surface layer and ageing of the binder in the surface course were identified as specific contributors to edge breakage, fatigue cracking, and raveling. The emergence of cracks results from the increased stiffness from the binder ageing process (Anderson et al. 2001).

Finally, the results suggest that drainability greatly influences the highway pavement's lifecycle structural performances; as Rasol et al. (2022) explain, water may enter between layers, accelerating asphalt interface degradation. In the design phase, inadequate surface drainage was ranked as one of the leading causes of fatigue cracking, bumps, and delamination. Such assertions are validated by Alber et al. (2020), Wang et al. (2018) and (Alber et al. 2020; Wang et al. 2018); Zhang et al. (2020). Poor drainage was also ranked the fourth most significant general cause of deterioration. Additionally, poorly designed subbase drainage was identified as a contributory factor to rutting, whereas poorly constructed surface drainage has been highlighted as a contributory factor to bumps, rutting, and delamination. The lifespan experts identified and ranked poorly maintained drains as the 16^{th} general cause of deterioration and a specific cause of longitudinal cracking.

Traffic

Traffic is considered the most important factor in pavement design (Huang 2004); this study’s design experts affirmed this position. Underestimated traffic loads and inadequate future traffic forecasts were ranked as the top two causes of pavement deterioration in the design phase. Also, vehicular traffic's phenomenal growth was ranked as the most significant cause of deterioration in the lifespan phase. In addition, the lack of control regarding the load limit carried by vehicles, over-weight vehicles and high traffic volume were ranked fourth, eighth and fourteenth respectively. Regarding the individual causes of distress, growth in vehicular traffic was ranked as the number one cause of fatigue cracking. Growth in vehicular traffic has predicted fatigue cracking performance (Dinegdae and Birgisson 2018). With a population of 1.4 million and over one million automobiles on the road, a predicted monthly vehicle growth of 2,000, and a vehicle density per 1000 person of 770 (Central Statistical Office 2019; Nanton 2019), increasing vehicle density on 8320 km of paved road might lead to traffic saturation or acute traffic constipation (‘stopping and standing traffic') (Shah 2014).

The resulting high traffic volume was identified as a cause of longitudinal cracking, transverse cracking, rutting, potholes, and delamination. The stopping and standing traffic’ was identified as a cause of rutting, which was also confirmed by Kandhal et al. (1998) in hot climates. Stopping and standing or even slow-moving traffic imposes greater damage than fast-moving traffic; for instance, an increased speed from 2 km/hr to 24 km/hr reduces the stress and pavement deflection by 40% (Chu 2010). Reversible stopping and standing traffic is currently a major problem observed daily during rush hours (6 am to 9 am and 3 pm to 6 pm) on the highways leading to and from Port of Spain city.

The pushing action by wheels of heavy vehicles at the time of acceleration and deceleration was identified by this study as a cause of shoving. In this scenario, the adhesion between adjacent layers is inadequate to produce the required shear strength to resist slippage under horizontal thrust (Kandhal et al. 1998). During traffic checks, 90% of trucks departing or entering the Solomon Hochoy Highway had loads exceeding their gross weight limit (MGW). They were sometimes 100% above their MGW (Felmine 2019). Overweight vehicles cause exponential pavement destruction (Luskin and Walton 2001), with pavement damage proportional to the vehicle's axle weight difference to the fourth power (IPWEA 2017). During the field survey, rutting and shoving were observed mostly at signalised intersections, where traffic was required to stop. This cause appears to be a combined effect of stopping heavy and overweight vehicles in the wheel path at signalised intersections.

The overloading issue is directly linked to the lack of control regarding the load limit of vehicles, as existing regulations provide for penalties. The problem is not non-existent control regulations but the enforcement of these regulations. First, the availability of weighbridges across the country is limited; as of February 2019, only three were reportedly functional (Felmine 2019), and second, enforcement exercises are arbitrary (Furlonge 2017). One of the delinquent drivers in those mentioned above "pull over" exercise expressed the unavailability of scales at pick-up locations as a major difficulty in adhering to the regulation (Felmine 2019).

Construction (Process)

The panel identified poor quality control as one of five general construction causes of pavement degradation. A pavement will not satisfy the required construction and performance requirements if all materials procedures, inspection, monitoring and testing are not carried out (Kuennen 2013), making it more probable for early failure. Outdated local standards lead to poor quality control but adopting international practice standards overlooks local variability such as aggregate specifications and environmental circumstances, making it improbable to obtain the desired quality.

Poor supervision and craftsmanship were rated third in overall pavement degradation. Poor craftsmanship indicates insufficient supervision and monitoring (Uff and Thornhill 2010) and management inadequacies (Hickson and Ellis 2014), features of which are common to Trinidad's construction industry. Bad communication, documentation, work system/methodology, worker performance, and planning may result from poor craftsmanship (Chong 2006).

The degree of compaction reflects the quality of supervision as it is essential to achieve the desired air void content as pavements with a high or low air-void content will not perform effectively. The respondents confirmed that insufficient surface/subbase/base compaction causes fatigue cracking, transverse cracking, rutting, depression, and ravelling. The amount of air gaps in a pavement affects its fatigue life, permanent deformation, oxidation, moisture damage, distortion, and disintegration. Reducing an asphalt mix's air-void percentage from 8% to 5% doubles fatigue life (Roy et al. 2013). Like permanent deformation (rutting and depression), lowering air-void content below 3% lowers the rutting rate (Brown and Cross 1992). Less air in the HMA material means slower oxidation but pavements become susceptible to water damage and ravelling with increased air above 8% Scherocman (2000). Reduced air-void content reduces distortion, especially while stopping or turning.

The base layer distributes the generated stresses from the traffic load and prevents the underlying subgrade from failing. Insufficient compacting of this layer reduces shear strength, stability and stiffness and increases permanent deformation (Titi et al. 2012). Inadequate initial density and shear strength allow for lateral movement of particles, resulting in rutting and depression (Saeed et al. 2001). High deflection in the HMA layer owing to base instability causes fatigue cracking.

The subbase, like the base, has to be rigid and robust to avoid deformation (rutting and depression) (Liley 2008), but Abd El Halim and Mostafa (2006) showed that compaction equipment like steel roller drums leads to early surface deterioration. Drum rollers increase permeability, layer permeability, and compaction near unsupported edges of paved lanes. However, the subgrade preparation should be adequate to deliver the required compaction and moisture content. Insufficient levels of these elements may cause excessive deformation (rutting) under high loads. Inadequate subgrade preparation causes shoving and potholes, weakening the bond between the pavement layers (Tamrakar 2019).

Longitudinal and transverse slopes affect surface drainage and, therefore, pavement deterioration. Sharp longitudinal slopes increase surface water movement and erosion. Flooding or ponding occurs when moderate transverse slopes or flat surfaces do not allow timely drainage. The quality of surface drainage is affected by collector drains. The pavement becomes saturated if collector drains are not deep enough (Sanborn 1963). Experts express that poor surface drainage causes bumps, rutting, and delamination.

Environment

Only in the lifespan phase were environmental elements recognised as degrading factors. Global warming, natural disasters, and moisture were all general causes of deterioration, with global warming placing in the top ten degradation causes. The effects of the increased temperatures are manifested on Trinidad's highways as fatigue cracking and ravelling. From 1961 to 2008, the meteorological data revealed that the average ambient temperature in Trinidad climbed by 1.7 ºC (Environmental Management Authority 2019). Heat accelerates the ageing of the binder, reducing asphalt durability and increasing its susceptibility to deterioration (Emery 2011; Wilway et al. 2008). The experts regarded the ageing of the surface course binder as the third most important cause of pavement degradation in-service. As pavements age, they become stiffer and more brittle as the stiffness modulus is lowered (Halle et al. 2012), increasing the risk of pavement failure (Lu et al. 2008). Rutting, corrugation, and shoving may have been caused by low rigidity modulus in combination with traffic, although they were not identified by this study as the specific cause of these distresses.

The Intergovernmental Panel on Climate Change (IPCC) (2007) predicts that severe weather events and heavy rains will increase in the Caribbean owing to global warming. Moisture damage to asphalt mixtures is proportional to water content Schmidt and Graf (1972). The effects are already seen from the four days of October 2018 flooding of the Uriah Butler Highway, causing structural damage to the pavement (Trinidad and Tobago Guardian 2018). Moisture may adversely affect the characteristics of pavement materials and hence, the overall structural performance of a pavement system (FHWA 2017). Water seepage via longitudinal joints has been linked to ravelling, potholes, and rutting. Moisture in the surface layer promotes stripping and loss of asphalt cement-aggregate adhesion (McGennis et al. 1984). Fatigue cracking and edge break were found as reasons for stripping on the HMA surface layer and loss of adhesion in the surface layer. ‘Trapped moisture in the lower layers of the pavement' causes rutting and weakens the surface (Bonaquist 2016). Base layer and subgrade moisture may also contribute to structural failure or movement of the bottom layers (fatigue cracking and depression). Trinidad's highways are also at danger from earthquakes. In August 2018, a 6.9 magnitude earthquake occured, and examining the nation's key roadways revealed minimal structural damage from the event (T&T News 2018).

Maintenance

‘Shortage of maintenance training activities’, ‘lack of supervision or supervision by unqualified personnel’, ‘insufficient funding’, ‘not involving local professional bodies in highway maintenance’, and ‘poorly maintained drains’ were identified as general deterioration causes resulting from poor maintenance. From 2019 to fiscal 2021, government funding for road construction and renovation fell 42%, while funding for municipal roads and bridges fell 20%. Due to a lack of funding for road repair, many of the roads under the government agency's jurisdiction require rehabilitation. Experts believe that maintenance does not significantly affect Trinidad's pavement deterioration compared to the other major general factors since the mentioned factors received low rankings (see Table 9). In addition to these factors, untimely maintenance was inferred from potholes' leading cause (the result of fatigue cracking). Failure to promptly repair fatigue cracks worsens the severity. As a result, the interconnected cracks form small chunks of dislodged pavement from vehicles that drive over them, resulting in potholes.

Practical lifecycle recommendations

This research highlighted the surface and subgrade layers as the most problematic pavement components because of their many contributions to deterioration. The causes of deterioration related to the surface layer included inadequacies in the bitumen mix's properties and content, aggregates, drainage, layer thickness, compaction, and material degradation. In examining the layers, the subgrade was deemed problematic due to its unstable or expansive behaviour, and it was identified as the leading contributor to eight distresses. After characterising highway pavement deterioration manifestations and determining their corresponding causes, several 'remedies' are proposed to improve highway pavements' longevity. The proposed design phase measures include pavement design reviews performed exclusively by local experienced and knowledgeable engineers, continuous knowledge improvement for pavement design engineers, improved accuracy of design considerations (traffic data and soil conditions), improved designs for pavement (surface and subbase) drainage and longitudinal joints between adjoining pavement layers, proper material specifications (aggregates and binder), changes to intersectional traffic control methods (grade-separated intersection control is favoured), and adoption of design strategies to make future pavements adaptable to global warming impacts. For the construction phase, recommendations are made for agencies to upgrade the local standards and specifications, embody quality within their value system, adopt a quality-based selection approach for contractors, and cater to adequate construction supervision independent of the contractor (FIDIC 2004). Contractors are also implored to embrace advanced technologies in the field, which will reduce pavement deterioration. Technologies such as the asphalt multi-integrated roller (AMIR) have significantly reduced pavements' deterioration.

Lastly, in the lifespan phase, measures to preserve the pavements include reducing the pavement loading (traffic weight and volume), protecting the pavements from environmental factors, and improving maintenance practices. Checks for overweight vehicles need to be consistent and not sporadic by implementing an in-road weight in motion (WIM) system similar to the existing spot speed camera system. The WIM system allows for simultaneous dynamic weighing of vehicles and photographic recording 24/7 (Traffic Data Systems 2019). In cases where vehicles are found to be overloaded, they should be required to off-load excess goods to another vehicle and not allowed to proceed until the weight limit is satisfied. Implementing car usage control strategies such as an Area License Scheme (ALS) or an Electric Road Pricing System (ERP) reduce high traffic volume. An ALS discourages vehicles from entering congested central areas during peak hours. This scheme has reportedly caused traffic flow during peak hours to drop by 40% in Singapore (Lam and Toan 2006).

Similarly, the ERP system motivates drivers to avoid certain areas at peak hours by changing modes of transport, route, or travel time. This system is based on the pay-as-you-use principle. To curtail the phenomenal growth of vehicular traffic, agencies can control private transportation demand by altering the existing menu of taxes for vehicle importation and /or considering a car ownership control strategy, such as Singapore's Vehicle Quota Scheme' (VQS). Such approaches can push the price so high that only those with the highest willingness to pay can own a car (Koh and Lee 1994; Land Transport Authority 2015; Trinh Toan 2018). Pavements can be protected from increased temperature using pavement surface reflectance technologies that do not require altering the existing pavement structure. Such heat-blocking coating technology applied on the pavement surface reduces the surface temperature by 10^0C or more. Measures to reduce water ingress into the pavement structure include routine drainage maintenance and repairing distress (especially cracks) as soon as they arise and as reported by citizens. Finally, the distress manual used by agencies for highway maintenance needs to be updated. The current version does not present all of the distresses on highways in Trinidad. Additionally, the defined causes of these distresses are ambiguous, and there are no defined distress severity levels.

Conclusion

This study examined pavement conditions along the east-west transportation corridor of Trinidad. Three panels of 24 specialists engaged in highway design, construction, and maintenance phases identified and rated the particular causes of pavement distress, as well as the overall reasons for pavement deterioration. This study used an advanced method to address the global and local issues of inadequate HMA pavement degradation data. It is the first in the field to comprehensively address pavement deterioration throughout the design, construction, and lifespan phases. Considering just one phase of the lifecycle, as in most existing studies, does not adequately address the issue of pavement degradation. Unlike historical documents and expensive field investigations, this method relied on professional knowledge gained through time. With the help of a group of specialists, the fuzzy-Delphi method facilitates the sharing of scientific or technical information. This comprehensive method may be used in developing nations when studies are expensive and there is a need to reduce traditional deterioration factor ambiguity by specifying the origin phase.

With the help of design, construction, and maintenance specialists, this research addressed the indistinctness associated with insufficient drainage. The design panel agreed that poor surface drainage was a deterioration factor, but it was excluded in the other two phases. This detailed analysis of deterioration reasons is very useful for designing and building new roadway pavements. This information will enhance the accuracy of flexible pavement failure prediction models, allowing for better construction and quality control procedures. Understanding flexible pavement distresses, and their sources can help preserve them. Furthermore, improved maintenance and rehabilitation operations planning may save substantial money for infrastructure management organisations (Li 2005).

Overall, the lifespan phase had the most contributions, almost twice as many as the design and building stages. However, the results indicate that most lifespan degradation is due to inadequacies in earlier stages. Experts agree that ‘structure', ‘traffic', ‘construction', ‘environment', and ‘maintenance' are significant contributors to pavement degradation, with structural factors predominating. All distress has structural causes (from all three stages). Similarly, six design phase contributions were structural for general aspects, while four were structural for construction and lifespan. Traffic issues were recognised as the second leading cause of pavement deterioration. Traffic throughout the lifespan or user phase was recognised as a factor in several distresses. Similarly, the two most important causes of pavement degradation in the design phase were traffic-related, which was likewise the top and fourth most significant reason in the lifespan phase. Environmental and maintenance reasons for deterioration were only addressed in the lifespan phase and heralded a need for earlier consideration. In addition to improving pavement performance prediction models, researchers may also enhance construction and maintenance methods. This research suggests ways to extend the life of HMA pavements in the tropics by reducing distress vulnerabilities.

Limitations and future research

More studies are needed to understand the interplay of pavement degradation causes. Understanding how these variables interact is essential to understanding how they affect pavement deterioration. Due to limited field studies, specific reasons for degradation for many identified distresses were not found; further work should be done to address this deficiency. With so many deterioration reasons, finding effective remedies proved difficult.

Conflict of interest

The authors declare that there is no conflict of interest or ethical issues regarding the publication of this manuscript.

Data availability

All Fuzzy data, models, or codes that support the findings of this study are available from the corresponding author.

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Table 1: Panel of highway pavement design, construction, and lifespan experts

Organization	Position/Role	Years of Experience	Highest level Academic Achievement
Design Experts			
Trintoplan Consultants Limited	Managing Director	33	MSc
Trintoplan Consultants Limited	Civil Engineer	2	BSc
Trintoplan Consultants Limited	Civil Engineer	8	MSc
Danny's Enterprises Company Ltd	Civil Engineer Consultant	9	MSc
HM Engineering and Construction Ltd.	Director	4	PhD
Beston Consulting Limited	Civil Engineer	5	BSc
Super pave Ltd	Civil Engineer	50	Postgraduate Diploma
KallCo	Senior Project Engineer	20	BSc
CARIRI (Caribbean Industrial Research Institute)*	Department Lab Manager/Senior Technician	37	BSc
The University of the West Indies	Lecturer	11	MSc
Construction Experts			
Ministry of Works & Transport (Highways Division)	Civil Engineer I	8	MSc
Ministry of Works & Transport* (Highways Division)	Civil Engineer I	2	BSc
Ministry of Works & Transport* (Highways Division)	Civil Engineer	7	MSc
Ministry of Works & Transport (Highways Division)	Chief Planning Engineer (Ag)	10	-
Ministry of Works & Transport (Highways Division)	Civil Engineer II (Ag)	14	-
Ministry of Works & Transport* (St. George West District)	Engineer Assistant III	1	Diploma/Associate Degree
Ministry of Works & Transport* (St. George East District)	Works Supervisor	5	Diploma/Associate Degree
Ministry of Works & Transport* (St. George East District)	Civil Engineer II	15	MSc
Ministry of Works & Transport (St. George East District)	District Engineer	5	BSc
Ministry of Works & Transport* (Caroni District)	Works Supervisor I	2	BSc
Super pave Ltd	Civil Engineer	50	Postgraduate Diploma
CARIRI (Caribbean Industrial Research Institute)	Laboratory Manager	10	MSc
HM Engineering and Construction Ltd.	Director	4	PhD
Lifespan Experts			
Ministry of Works & Transport (PURE – Programme for Upgrading Roads Efficiency)	Senior Project Manager		MSc
Ministry of Works & Transport* (PURE – Programme for Upgrading Roads Efficiency)	Associate Engineer	4	BSc
Ministry of Works & Transport (PURE – Programme for Upgrading Roads Efficiency)	Project Engineer	9	BSc
Ministry of Works & Transport (PURE – Programme for Upgrading Roads Efficiency)	Project Engineer	5	BSc
Ministry of Works & Transport (PURE – Programme for Upgrading Roads Efficiency)	Project Manager	-	-
Ministry of Works & Transport (PURE – Programme for Upgrading Roads Efficiency)	Project Manager	12	BSc
Ministry of Works & Transport (PURE – Programme for Upgrading Roads Efficiency)	Construction Technician	25	Diploma/Associate Degree
Ministry of Works & Transport (St. George East District)	Civil Engineer II	15	MSc
Ministry of Works & Transport (St. George East District)*	Works Supervisor I	2	Diploma/Associate Degree
Ministry of Works & Transport (St. George East District)*	Civil Engineer I	5	BSc
Ministry of Works & Transport (Caroni District)*	Works Supervisor I	2	BSc
Ministry of Works & Transport (Caroni District)*	Civil Engineer	15	BSc
Super pave Ltd	Civil Engineer	50	Postgraduate Diploma

- **Indicates persons dropping out after the first stage**

Table 2: Triangular fuzzy spectrum for a seven-point Likert

Likert Scale	Linguistic Variables (Shortening in lifespan - years)	Triangular Fuzzy Number (TFN) (Habibi, Jahantigh and Sarafrazi 2015)
1	0	(0.00,0.00,0.10)
2	0 to 1	(0.00,0.10,0.30)
3	1 to 2	(0.10, 0.30,0.50)
4	2 to 3	(0.30,0.50,0.75)
5	3 to 4	(0.50, 0.75,0.9)
6	4 to 5	(0.75,0.90,1.00)
7	> 5	(0.90,1.00,1.00)

Table 3: Identified distresses and severity in westbound and eastbound directions

Ref.	Section: From	Section: To	Fatigue	Longitudinal	Transverse	Block	Slippage	Reflective	Edge	Meandering	Diagonal	Rutting	Corrugations	Shoving	Depressions	Swells/ Upheaval	Bumps	Potholes	Patches	Raveling	Asphalt bleeding	Water bleeding	Water pumping	Polishing	Delamination	Edge Break	Edge drop off	Fatigue	Longitudinal
East Bound																													
AB	South Quay Lighthouse	Beetham/POS Flyover	c	c		*						c						c	c								c	c	
BC	Beetham/POS Flyover	Barataria Overpass	c	c		*				c				c				c		c				a			c	c	
CD	Barataria Overpass	Uriah Butler Highway	c	c						c		*	*	c			c	*	*					a			c	c	
DE	Uriah Butler Highway	Southern Main Rd. Intersection	c									c			*		*	c			*			a	*		c		
EF	Southern Main Rd. Intersection	College Road													*					c				a		c			
FG	College Road	Macoya	b	c	c							c	*	c	c		*	*	c	b				a	c		b	c	c
GH	Macoya	Trincity	c	c								c		c	c				c								c	c	
HI	Trincity	Golden Grove Road				*						*			*									a					
IJ	Golden Grove Road	Mausica Road	*	c						c		*	*														*	c	
West Bound																													
BA	Beetham/POS Flyover	South Quay Lighthouse		c								b					c	c	c					a				c	
CB	Barataria Overpass	Beetham/POS Flyover	c	c	*					b										c	c						c	c	*
DC	Uriah Butler Highway	Barataria Overpass	*	c	*									c	c			*	c					a		*	*	c	*
ED	Southern Main Rd. Intersection	Uriah Butler Highway										c		c				*	c					a					
FE	College Road	Southern Main Rd.		c								c								c	c							c	
GF	Macoya	College Road	c	c	c							*		c				c						a			c	c	c
HG	Trincity	Macoya	c	c		*				c					*		*	c	c	c				a	c		c	c	
IH	Golden Grove Road	Trincity	c	c														b		c					*		c	c	
JI	Mausica Road	Golden Grove Road	c	c		*				c		c		*			c	c			*			a	c		c	c	

KEY

a No Severity
c Medium Severity
* Low Severity
b High Severity

Table 4: Fuzzy triangular numbers by design experts

Factors	Expert 1			Expert 2			Expert 3			Expert 4			Expert 5			Expert 6			Expert 7			Expert 8			Expert 9		
Structure																											
Inadequate thickness of pavement layers	0.90	1.00	1.00	0.30	0.50	0.75	0.90	1.00	1.00	0.90	1.00	1.00	0.10	0.30	0.50	0.10	0.30	0.50	0.10	0.30	0.50	0.10	0.30	0.50	0.90	1.00	1.00
Inadequate base thickness	0.90	1.00	1.00	0.90	1.00	1.00	0.50	0.75	0.90	0.90	1.00	1.00	0.10	0.30	0.50	0.10	0.30	0.50	0.30	0.50	0.75	0.10	0.30	0.50	0.75	0.90	1.00
Inadequate sub base thickness	0.90	1.00	1.00	0.90	1.00	1.00	0.75	0.90	1.00	0.90	1.00	1.00	0.10	0.30	0.50	0.30	0.50	0.75	0.30	0.50	0.75	0.10	0.30	0.50	0.00	0.10	0.30
Inadequate pavement mix design	0.50	0.75	0.90	0.30	0.50	0.75	0.10	0.30	0.50	0.90	1.00	1.00	0.75	0.90	1.00	0.10	0.30	0.50	0.00	0.10	0.30	0.10	0.30	0.50	0.90	1.00	1.00
Inadequate preliminary geological investigation	0.50	0.75	0.90	0.50	0.75	0.90	0.30	0.50	0.75	0.90	1.00	1.00	0.90	1.00	1.00	0.30	0.50	0.75	0.00	0.00	0.10	0.10	0.30	0.50	0.50	0.75	0.90
Inadequate design knowledge	0.75	0.90	1.00	0.50	0.75	0.90	0.75	0.90	1.00	0.90	1.00	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.00	0.10	0.30	0.10	0.30	0.50	0.00	0.10	0.30
Inadequate surface drainage	0.90	1.00	1.00	0.50	0.75	0.90	0.90	1.00	1.00	0.90	1.00	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.30	0.50	0.75	0.10	0.30	0.50	0.30	0.50	0.75
Poor drainability of the subbase	0.75	0.90	1.00	0.90	1.00	1.00	0.75	0.90	1.00	0.90	1.00	1.00	0.75	0.90	1.00	0.10	0.30	0.50	0.30	0.50	0.75	0.10	0.30	0.50	0.00	0.10	0.30
Inadequate pavement design for soil condition	0.90	1.00	1.00	0.90	1.00	1.00	0.50	0.75	0.90	0.90	1.00	1.00	0.90	1.00	1.00	0.30	0.50	0.75	0.30	0.50	0.75	0.10	0.30	0.50	0.90	1.00	1.00
Weak joints between the adjoining spread of pavement layers	0.90	1.00	1.00	0.30	0.50	0.75	0.10	0.30	0.50	0.90	1.00	1.00	0.10	0.30	0.50	0.10	0.30	0.50	0.00	0.00	0.10	0.00	0.10	0.30	0.10	0.30	0.50
Inadequate stability of the subgrade or sub-base or base course	0.90	1.00	1.00	0.50	0.75	0.90	0.30	0.50	0.75	0.90	1.00	1.00	0.30	0.50	0.75	0.10	0.30	0.50	0.30	0.50	0.75	0.10	0.30	0.50	0.00	0.10	0.30
Weak pavement structure	0.90	1.00	1.00	0.90	1.00	1.00	0.50	0.75	0.90	0.90	1.00	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.00	0.10	0.30	0.00	0.10	0.30	0.75	0.90	1.00
An excess of asphalt in the top layer	0.00	0.00	0.10	0.30	0.50	0.75	0.00	0.10	0.30	0.90	1.00	1.00	0.00	0.10	0.30	0.00	0.00	0.10	0.00	0.00	0.10	0.00	0.10	0.30	0.90	1.00	1.00
Faulty design Parameters	0.90	1.00	1.00	0.75	0.90	1.00	0.90	1.00	1.00	0.90	1.00	1.00	0.75	0.90	1.00	0.00	0.10	0.30	0.10	0.30	0.50	0.00	0.10	0.30	0.75	0.90	1.00
Inappropriate design procedures	0.90	1.00	1.00	0.50	0.75	0.90	0.75	0.90	1.00	0.90	1.00	1.00	0.10	0.30	0.50	0.00	0.10	0.30	0.00	0.10	0.30	0.00	0.10	0.30	0.10	0.30	0.50
Relatively high fines/asphalt (F/A) ratio	0.00	0.10	0.30	0.30	0.50	0.75	0.30	0.50	0.75	0.90	1.00	1.00	0.00	0.10	0.30	0.00	0.10	0.30	0.30	0.50	0.75	0.00	0.10	0.30	0.50	0.75	0.90
Lack of stability in the bitumen mix	0.10	0.30	0.50	0.30	0.50	0.75	0.90	1.00	1.00	0.90	1.00	1.00	0.10	0.30	0.50	0.00	0.10	0.30	0.30	0.50	0.75	0.00	0.10	0.30	0.90	1.00	1.00
Inadequate pavement structure	0.90	1.00	1.00	0.75	0.90	1.00	0.75	0.90	1.00	0.90	1.00	1.00	0.75	0.90	1.00	0.00	0.10	0.30	0.10	0.30	0.50	0.10	0.30	0.50	0.90	1.00	1.00
Insufficient adhesion between the asphalt cement and the aggregates	0.30	0.50	0.75	0.30	0.50	0.75	0.90	1.00	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.00	0.10	0.30	0.30	0.50	0.75	0.00	0.10	0.30	0.00	0.10	0.30
Aggregates not hard enough	0.10	0.30	0.50	0.30	0.50	0.75	0.50	0.75	0.90	0.90	1.00	1.00	0.00	0.10	0.30	0.00	0.10	0.30	0.30	0.50	0.75	0.00	0.10	0.30	0.10	0.30	0.50
Traffic																											
Underestimated traffic loads	0.90	1.00	1.00	0.90	1.00	1.00	0.90	1.00	1.00	0.90	1.00	1.00	0.90	1.00	1.00	0.10	0.30	0.50	0.30	0.50	0.75	0.10	0.30	0.50	0.90	1.00	1.00
Inadequate future traffic forecast	0.90	1.00	1.00	0.75	0.90	1.00	0.50	0.75	0.90	0.90	1.00	1.00	0.90	1.00	1.00	0.10	0.30	0.50	0.30	0.50	0.75	0.00	0.10	0.30	0.90	1.00	1.00
Geometric Design																											
Poor alignment	0.50	0.75	0.90	0.90	1.00	1.00	0.00	0.10	0.30	0.90	1.00	1.00	0.00	0.00	0.10	0.00	0.00	0.10	0.00	0.00	0.10	0.00	0.10	0.30	0.00	0.10	0.30
Inadequate pavement width	0.00	0.00	0.10	0.50	0.75	0.90	0.30	0.50	0.75	0.90	1.00	1.00	0.00	0.10	0.30	0.10	0.30	0.50	0.00	0.00	0.10	0.00	0.10	0.30	0.10	0.30	0.50
Inadequate edge support	0.30	0.50	0.75	0.50	0.75	0.90	0.90	1.00	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.00	0.10	0.30	0.10	0.30	0.50	0.10	0.30	0.50	0.10	0.30	0.50
Other																											
Not involving local professional bodies in highway construction	0.30	0.50	0.75	0.75	0.90	1.00	0.00	0.10	0.30	0.90	1.00	1.00	0.00	0.10	0.30	0.00	0.00	0.10	0.00	0.00	0.10	0.00	0.10	0.30	0.00	0.00	0.10

Table 5: Fuzzy triangular numbers by construction experts

Factors	Expert 1			Expert 2			Expert 3			Expert 4			Expert 5			Expert 6			Expert 7		
Construction Process																					
Inadequate compaction (surface/ subbase / base)	0.75	0.90	1.00	0.75	0.90	1.00	0.00	0.10	0.30	0.50	0.75	0.90	0.90	1.00	1.00	0.10	0.30	0.50	0.75	0.90	1.00
Compaction procedure (use of conventional steel drum roller)	0.50	0.75	0.90	0.30	0.50	0.75	0.00	0.10	0.30	0.30	0.50	0.75	0.50	0.75	0.90				0.50	0.75	0.90
Incorrect blending of binder	0.50	0.75	0.90	0.30	0.50	0.75	0.10	0.30	0.50	0.30	0.50	0.75	0.75	0.90	1.00				0.75	0.90	1.00
Construction during wet weather	0.30	0.50	0.75	0.90	1.00	1.00	0.00	0.10	0.30	0.10	0.30	0.50	0.75	0.90	1.00				0.00	0.10	0.30
Poor laboratory and in-situ tests on subgrade soil	0.30	0.50	0.75	0.50	0.75	0.90	0.00	0.10	0.30	0.30	0.50	0.75	0.50	0.75	0.90	0.10	0.30	0.50	0.10	0.30	0.50
Low knowledge base	0.50	0.75	0.90	0.75	0.90	1.00	0.00	0.10	0.30	0.10	0.30	0.50	0.50	0.75	0.90				0.90	1.00	1.00
Poor supervision and workmanship	0.75	0.90	1.00	0.75	0.90	1.00	0.00	0.10	0.30	0.10	0.30	0.50	0.75	0.90	1.00	0.90	1.00	1.00	0.75	0.90	1.00
Poor quality control	0.75	0.90	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.30	0.50	0.75	0.75	0.90	1.00	0.90	1.00	1.00	0.75	0.90	1.00
Poor local standard of practice	0.75	0.90	1.00	0.10	0.30	0.50	0.00	0.10	0.30	0.10	0.30	0.50	0.30	0.50	0.75	0.90	1.00	1.00	0.90	1.00	1.00
Varying composition of mix delivered to site (gradation; asphalt content; voids)	0.75	0.90	1.00	0.30	0.50	0.75	0.10	0.30	0.50	0.50	0.75	0.90	0.30	0.50	0.75				0.75	0.90	1.00
Brittle binder due to initial overheating	0.50	0.75	0.90	0.90	1.00	1.00	0.00	0.10	0.30	0.30	0.50	0.75	0.75	0.90	1.00				0.75	0.90	1.00
Low (placement) temperature of bitumen	0.50	0.75	0.90	0.90	1.00	1.00	0.00	0.10	0.30	0.30	0.50	0.75	0.90	1.00	1.00				0.50	0.75	0.90
Faulty laying of surface course	0.30	0.50	0.75	0.30	0.50	0.75	0.00	0.10	0.30	0.75	0.90	1.00	0.30	0.50	0.75				0.50	0.75	0.90
Unstable or inadequately prepared subgrade	0.10	0.30	0.50	0.50	0.75	0.90	0.10	0.30	0.50	0.75	0.90	1.00	0.90	1.00	1.00	0.10	0.30	0.50	0.10	0.30	0.50
Structure																					
Use of low-quality construction materials	0.75	0.90	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.30	0.50	0.75	0.30	0.50	0.75	0.10	0.30	0.50	0.90	1.00	1.00
Low stiffness of constructed base	0.50	0.75	0.90	0.50	0.75	0.90	0.10	0.30	0.50	0.30	0.50	0.75	0.90	1.00	1.00	0.90	1.00	1.00	0.75	0.90	1.00
Use of inappropriate aggregates (hydrophilic; naturally smooth uncrushed; dusty)	0.75	0.90	1.00	0.75	0.90	1.00	0.10	0.30	0.50	0.30	0.50	0.75	0.50	0.75	0.90	0.30	0.50	0.75	0.90	1.00	1.00
Inadequate strength (stability) in surface/base layers	0.75	0.90	1.00	0.50	0.75	0.90	0.00	0.10	0.30	0.10	0.30	0.50	0.90	1.00	1.00	0.30	0.50	0.75	0.90	1.00	1.00
Poor bond between pavement layers	0.50	0.75	0.90	0.75	0.90	1.00	0.00	0.10	0.30	0.10	0.30	0.50	0.90	1.00	1.00	0.00	0.00	0.10	0.90	1.00	1.00
Poor binder to stone adhesion	0.75	0.90	1.00	0.50	0.75	0.90	0.10	0.30	0.50	0.10	0.30	0.50	0.30	0.50	0.75	0.00	0.00	0.10	0.75	0.90	1.00
Low binder content	0.50	0.75	0.90	0.50	0.75	0.90	0.00	0.10	0.30	0.30	0.50	0.75	0.75	0.90	1.00	0.00	0.00	0.10	0.75	0.90	1.00
Less bitumen content in localised areas	0.50	0.75	0.90	0.30	0.50	0.75	0.10	0.30	0.50	0.30	0.50	0.75	0.50	0.75	0.90	0.00	0.00	0.10	0.75	0.90	1.00
Low penetration value of the binder content	0.50	0.75	0.90	0.50	0.75	0.90	0.00	0.10	0.30	0.10	0.30	0.50	0.30	0.50	0.75	0.00	0.00	0.10	0.75	0.90	1.00
Stiff asphalt mixture	0.50	0.75	0.90	0.50	0.75	0.90	0.00	0.10	0.30	0.10	0.30	0.50	0.30	0.50	0.75	0.00	0.00	0.10	0.75	0.90	1.00
Relatively high Fines/Asphalt (F/A) ratio	0.50	0.75	0.90	0.30	0.50	0.75	0.10	0.30	0.50	0.00	0.10	0.30	0.75	0.90	1.00				0.75	0.90	1.00
Bitumen hardening in asphalt surfacing	0.50	0.75	0.90	0.50	0.75	0.90	0.00	0.10	0.30	0.00	0.10	0.30	0.75	0.90	1.00				0.75	0.90	1.00
Construction joints (between the adjoining spread of pavement layers; bridges)	0.50	0.75	0.90	0.30	0.50	0.75	0.00	0.10	0.30	0.00	0.10	0.30	0.10	0.30	0.50	0.00	0.00	0.10	0.75	0.90	1.00
Too thin bituminous surface	0.50	0.75	0.90	0.75	0.90	1.00	0.10	0.30	0.50	0.10	0.30	0.50	0.10	0.30	0.50				0.75	0.90	1.00
Thin asphalt layer over bridges	0.50	0.75	0.90	0.75	0.90	1.00	0.10	0.30	0.50	0.10	0.30	0.50	0.10	0.30	0.50				0.75	0.90	1.00
Poor drainability of the subbase	0.90	1.00	1.00	0.75	0.90	1.00	0.00	0.10	0.30	0.00	0.10	0.30	0.90	1.00	1.00	0.75	0.90	1.00	0.90	1.00	1.00
An excess of asphalt in the top layer	0.75	0.90	1.00	0.50	0.75	0.90	0.10	0.30	0.50	0.00	0.10	0.30	0.10	0.30	0.50				0.50	0.75	0.90
Inadequate surface drainage	0.50	0.75	0.90	0.75	0.90	1.00	0.10	0.30	0.50	0.00	0.10	0.30	0.90	1.00	1.00	0.10	0.30	0.50	0.75	0.90	1.00
Using low viscosity binder	0.50	0.75	0.90	0.50	0.75	0.90	0.00	0.10	0.30	0.10	0.30	0.50	0.10	0.30	0.50	0.90	1.00	1.00	0.75	0.90	1.00
Other																					
Not involving local professional bodies in highway construction	0.30	0.50	0.75	0.00	0.10	0.30	0.00	0.10	0.30	0.50	0.75	0.90	0.75	0.90	1.00	0.30	0.50	0.75	0.00	0.00	0.10
Poor laboratory facilities	0.50	0.75	0.90	0.10	0.30	0.50	0.00	0.10	0.30	0.30	0.50	0.75	0.10	0.30	0.50	0.30	0.50	0.75	0.00	0.10	0.30
Poorly trained laboratory man power	0.75	0.90	1.00	0.10	0.30	0.50	0.00	0.10	0.30	0.30	0.50	0.75	0.30	0.50	0.75	0.30	0.50	0.75	0.00	0.10	0.30

Table 6: Fuzzy triangular numbers by lifespan experts

Factors	Expert 1			Expert 2			Expert 3			Expert 4			Expert 5			Expert 6			Expert 7			Expert 8		
Traffic																								
Over-weight/ over-height vehicles	0.90	1.00	1.00	0.00	0.00	0.10	0.00	0.10	0.30	0.30	0.50	0.75	0.30	0.50	0.75	0.75	0.90	1.00	0.30	0.50	0.75	0.50	0.75	0.90
High traffic volume	0.90	1.00	1.00	0.90	1.00	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.90	1.00	1.00	0.00	0.00	0.10	0.90	1.00	1.00	0.90	1.00	1.00
Lack of control regarding load limit carried by vehicles	0.90	1.00	1.00	0.90	1.00	1.00	0.90	1.00	1.00	0.90	1.00	1.00	0.50	0.75	0.90	0.50	0.75	0.90	0.30	0.50	0.75	0.90	1.00	1.00
Phenomenal growth of vehicular traffic	0.75	0.90	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.90	1.00	1.00	0.00	0.10	0.30	0.50	0.75	0.90	0.30	0.50	0.75	0.90	1.00	1.00
Stopping & standing traffic	0.75	0.90	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.75	0.90	1.00	0.50	0.75	0.90	0.50	0.75	0.90	0.75	0.90	1.00	0.00	0.00	0.10
Pushing action by wheels of heavy traffic at the time of acceleration and deceleration	0.75	0.90	1.00	0.75	0.90	1.00				0.90	1.00	1.00	0.00	0.10	0.30	0.10	0.30	0.50	0.10	0.30	0.50	0.00	0.10	0.30
Traffic travelling on shoulder	0.75	0.90	1.00	0.75	0.90	1.00				0.30	0.50	0.75	0.90	1.00	1.00	0.10	0.30	0.50	0.00	0.00	0.10	0.00	0.00	0.10
Channelized movement of heavy wheel loads causing significant vertical stress on the subgrade	0.90	1.00	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.10	0.30	0.50	0.90	1.00	1.00	0.10	0.30	0.50	0.30	0.50	0.75	0.00	0.10	0.30
Environmental																								
Differential settlement	0.90	1.00	1.00	0.90	1.00	1.00	0.90	1.00	1.00	0.50	0.75	0.90	0.90	1.00	1.00	0.10	0.30	0.50	0.10	0.30	0.50	0.00	0.10	0.30
Seepage of water into the subgrade	0.75	0.90	1.00	0.75	0.90	1.00	0.75	0.90	1.00	0.75	0.90	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.10	0.30	0.50	0.00	0.10	0.30
Seepage of water through asphalt/longitudinal joints	0.75	0.90	1.00	0.75	0.90	1.00	0.75	0.90	1.00	0.75	0.90	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.75	0.90	1.00	0.00	0.10	0.30
Water pooling on surface	0.30	0.50	0.75	0.50	0.75	0.90	0.30	0.50	0.75	0.00	0.10	0.30	0.30	0.50	0.75	0.00	0.10	0.30	0.30	0.50	0.75	0.00	0.10	0.30
Unstable /Expansive subgrade soils	0.75	0.90	1.00	0.90	1.00	1.00				0.75	0.90	1.00	0.90	1.00	1.00	0.10	0.30	0.50	0.75	0.90	1.00	0.75	0.90	1.00
High ground water level	0.90	1.00	1.00	0.75	0.90	1.00	0.10	0.30	0.50	0.30	0.50	0.75	0.90	1.00	1.00	0.00	0.10	0.30	0.00	0.10	0.30	0.00	0.10	0.30
Natural disaster	0.75	0.90	1.00	0.90	1.00	1.00	0.00	0.00	0.10				0.90	1.00	1.00	0.10	0.30	0.50	0.00	0.10	0.30	0.00	0.10	0.30
Global warming	0.75	0.90	1.00	0.75	0.90	1.00	0.75	0.90	1.00	0.75	0.90	1.00	0.50	0.75	0.90	0.30	0.50	0.75	0.00	0.00	0.10	0.90	1.00	1.00
Climate fluctuations in temperature and precipitation	0.50	0.75	0.90	0.90	1.00	1.00	0.10	0.30	0.50	0.90	1.00	1.00	0.90	1.00	1.00	0.50	0.75	0.90	0.00	0.10	0.30	0.00	0.00	0.10
Trapped moisture in the bottom layers of the pavement	0.50	0.75	0.90	0.50	0.75	0.90	0.10	0.30	0.50	0.50	0.75	0.90	0.90	1.00	1.00	0.10	0.30	0.50	0.00	0.10	0.30	0.00	0.10	0.30
Structure																								
Deterioration of aggregates	0.75	0.90	1.00	0.90	1.00	1.00	0.50	0.75	0.90	0.90	1.00	1.00	0.90	1.00	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.90	1.00	1.00
Ageing of brittle base	0.75	0.90	1.00	0.75	0.90	1.00	0.50	0.75	0.90	0.90	1.00	1.00	0.75	0.90	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.00	0.10	0.30
Ageing of binder in the surface course	0.50	0.75	0.90	0.50	0.75	0.90	0.50	0.75	0.90	0.75	0.90	1.00	0.90	1.00	1.00	0.90	1.00	1.00	0.50	0.75	0.90	0.00	0.10	0.30
Loss of adhesion in the surface layer	0.75	0.90	1.00	0.50	0.75	0.90	0.50	0.75	0.90	0.30	0.50	0.75	0.50	0.75	0.90	0.90	1.00	1.00	0.10	0.30	0.50	0.00	0.10	0.30
Post-construction compaction	0.75	0.90	1.00	0.00	0.10	0.30	0.10	0.30	0.50	0.90	1.00	1.00	0.90	1.00	1.00	0.90	1.00	1.00				0.00	0.10	0.30
Structural failure of the bottom layers/movement of the bottom layers	0.90	1.00	1.00	0.90	1.00	1.00	0.10	0.30	0.50	0.10	0.30	0.50	0.90	1.00	1.00	0.30	0.50	0.75	0.00	0.10	0.30	0.00	0.10	0.30
Stripping on the bottom of the HMA surface layer	0.75	0.90	1.00	0.30	0.50	0.75				0.50	0.75	0.90	0.75	0.90	1.00	0.00	0.10	0.30	0.10	0.30	0.50	0.00	0.10	0.30
Shoulder settlement	0.75	0.90	1.00	0.90	1.00	1.00				0.90	1.00	1.00	0.30	0.50	0.75	0.30	0.50	0.75	0.00	0.00	0.10	0.00	0.00	0.10
Unstable base	0.90	1.00	1.00	0.90	1.00	1.00				0.30	0.50	0.75	0.90	1.00	1.00	0.90	1.00	1.00	0.10	0.30	0.50	0.10	0.30	0.50
Pavement widening	0.75	0.90	1.00	0.00	0.00	0.10				0.90	1.00	1.00	0.00	0.00	0.10	0.00	0.00	0.10	0.50	0.75	0.90	0.00	0.10	0.30
Inadequate surface drainage	0.50	0.75	0.90	0.75	0.90	1.00				0.75	0.90	1.00	0.75	0.90	1.00	0.10	0.30	0.50	0.00	0.10	0.30	0.00	0.10	0.30
Reflection of joints or shrink cracking in underlying layers	0.50	0.75	0.90	0.50	0.75	0.90				0.50	0.75	0.90	0.30	0.50	0.75	0.10	0.30	0.50	0.10	0.30	0.50	0.00	0.10	0.30
Maintenance																								
Lack of routine and periodic maintenance	0.75	0.90	1.00	0.90	1.00	1.00				0.75	0.90	1.00	0.90	1.00	1.00	0.30	0.50	0.75	0.30	0.50	0.75	0.90	1.00	1.00
Poor/Non-existence of updated guideline standards/specifications/policies/ norms	0.75	0.90	1.00	0.50	0.75	0.90				0.10	0.30	0.50	0.30	0.50	0.75	0.30	0.50	0.75	0.10	0.30	0.50	0.00	0.10	0.30
Poor maintenance culture	0.75	0.90	1.00	0.90	1.00	1.00				0.00	0.10	0.30	0.90	1.00	1.00	0.30	0.50	0.75	0.00	0.10	0.30	0.90	1.00	1.00
Lack of supervision or supervision by unprofessional personnel	0.75	0.90	1.00	0.90	1.00	1.00				0.00	0.10	0.30	0.90	1.00	1.00	0.30	0.50	0.75	0.00	0.10	0.30	0.00	0.10	0.30
Insufficient funding	0.75	0.90	1.00	0.75	0.90	1.00				0.00	0.10	0.30	0.30	0.50	0.75	0.75	0.90	1.00	0.10	0.30	0.50	0.00	0.10	0.30
Lack of and shortage of qualified maintenance engineers	0.75	0.90	1.00	0.30	0.50	0.75				0.30	0.50	0.75	0.30	0.50	0.75	0.10	0.30	0.50	0.10	0.30	0.50	0.00	0.10	0.30
Delayed maintenance during their service life until they reach the state of major failure that requires rehabilitation	0.75	0.90	1.00	0.90	1.00	1.00				0.10	0.30	0.50	0.90	1.00	1.00	0.10	0.30	0.50	0.10	0.30	0.50	0.00	0.10	0.30

Exclusion of preventative maintenance from the maintenance policy	0.90	1.00	1.00	0.90	1.00	1.00	0.10	0.30	0.50	0.90	1.00	1.00	0.10	0.30	0.50	0.10	0.30	0.50	0.90	1.00	1.00
Poor management of maintenance works and activities	0.90	1.00	1.00	0.75	0.90	1.00	0.10	0.30	0.50	0.90	1.00	1.00	0.10	0.30	0.50	0.30	0.50	0.75	0.90	1.00	1.00
Shortage of maintenance training activities	0.90	1.00	1.00	0.10	0.30	0.50	0.90	1.00	1.00	0.30	0.50	0.75	0.10	0.30	0.50	0.30	0.50	0.75	0.90	1.00	1.00
Lack of modern technology	0.75	0.90	1.00	0.30	0.50	0.75	0.90	1.00	1.00	0.30	0.50	0.75	0.00	0.00	0.10	0.30	0.50	0.75			
Shortage of skilled equipment labor	0.75	0.90	1.00	0.30	0.50	0.75	0.30	0.50	0.75	0.30	0.50	0.75	0.10	0.30	0.50	0.10	0.30	0.50	0.00	0.10	0.30
Insufficient machines and equipment for maintenance works	0.75	0.90	1.00	0.30	0.50	0.75	0.10	0.30	0.50	0.90	1.00	1.00	0.10	0.30	0.50	0.10	0.30	0.50	0.00	0.10	0.30
Severe shortage in the required spare parts for maintenance machines	0.50	0.75	0.90	0.75	0.90	1.00	0.10	0.30	0.50	0.50	0.75	0.90	0.10	0.30	0.50	0.10	0.30	0.50	0.00	0.10	0.30
Poorly maintained drains	0.75	0.90	1.00	0.90	1.00	1.00	0.00	0.10	0.30	0.90	1.00	1.00	0.10	0.30	0.50	0.00	0.10	0.30	0.00	0.00	0.10
Filling holes inadequately (without cleaning and preparation, etc.)				0.75	0.90	1.00	0.10	0.30	0.50	0.50	0.75	0.90	0.10	0.30	0.50	0.00	0.00	0.10	0.00	0.10	0.30
Not involving local professional bodies in highway maintenance	0.30	0.50	0.75	0.90	1.00	1.00	0.50	0.75	0.90	0.00	0.00	0.10	0.00	0.00	0.10	0.10	0.30	0.50	0.90	1.00	1.00
End result of fatigue cracking	0.75	0.90	1.00	0.90	1.00	1.00	0.50	0.75	0.90	0.50	0.75	0.90	0.50	0.75	0.90	0.10	0.30	0.50	0.90	1.00	1.00

Table 7: Aggregated and ranked defuzzified factors

DESIGN FACTORS	$\widetilde{w}_J$ (a,b,c)	S_J (Crisp Value)
Structure		
Inadequate thickness of pavement layers	(0.10,0.63,1.00)	0.606
Inadequate base thickness	(0.10,0.67,1.00)	0.631
Inadequate preliminary geological investigation	(0.00,0.62,1.00)	0.578
Inadequate design knowledge	(0.00,0.57,1.00)	0.548
Inadequate surface drainage	(0.00,0.68,1.00)	0.622
Poor drainability of the subbase	(0.00,0.66,1.00)	0.604
Inadequate pavement design for soil condition	(0.10,0.78,1.00)	0.706
Weak joints between the adjoining spread of pavement layers	(0.00,0.42,1.00)	0.448
An excess of asphalt in the top layer*	(0.00,0.31,1.00)	0.374
Faulty design Parameters	(0.10,0.69,1.00)	0.626
Lack of stability in the bitumen mix	(0.00,0.53,1.00)	0.522
Inadequate pavement structure	(0.00,0.71,1.00)	0.641
Aggregates not hard enough*	(0.00,0.41,1.00)	0.437
Traffic		
Underestimated traffic loads	(0.10,0.79,1.00)	0.709
Inadequate future traffic forecast	(0.00,0.73,1.00)	0.652
Geometric Design		
Poor alignment*	(0.00,0.34,1.00)	0.393
Other		
Not involving local professional bodies in highway design*	(0.00,0.30,1.00)	0.367
CONSTRUCTION FACTORS		
Construction Process		
Inadequate compaction (surface/ subbase / base)	(0.00,0.69,1.00)	0.629
Compaction procedure (use of conventional steel drum roller)	(0.00,0.56,0.90)	0.522
Poor laboratory and in-situ tests on subgrade soil*	(0.00,0.46,0.90)	0.455
Poor supervision and workmanship	(0.00,0.71,1.00)	0.643
Poor quality control	(0.00,0.76,1.00)	0.671
Poor local standard of practice	(0.00,0.59,1.00)	0.557
Unstable or inadequately prepared subgrade	(0.10,0.55,1.00)	0.550
Structure		
Use of inappropriate aggregates (hydrophilic; naturally smooth uncrushed; dusty)	(0.10,0.69,1.00)	0.645
Poor bond between pavement layers	(0.00,0.58,1.00)	0.552
Poor binder to stone adhesion	(0.00,0.52,1.00)	0.514
Low binder content	(0.00,0.34,1.00)	0.538
Low penetration value of the binder content*	(0.00,0.47,1.00)	0.481
Stiff asphalt mixture*	(0.00,0.47,1.00)	0.481
Too thin bituminous surface	(0.10,0.58,1.00)	0.567
Thin asphalt layer over bridges	(0.10,0.58,1.00)	0.567
Poor drainability of the subbase	(0.00,0.71,1.00)	0.643
Inadequate surface drainage	(0.00,0.61,1.00)	0.571
Other		
Not involving local professional bodies in highway design*	(0.00,0.41,1.00)	0.443
LIFESPAN FACTORS		
Traffic		
Over-weight/ over-height vehicles	(0.00,0.69,1.00)	0.629
High traffic volume	(0.00,0.51,1.00)	0.508
Lack of control regarding load limit carried by vehicles	(0.00,0.79,1.00)	0.696
Phenomenal growth of vehicular traffic	(0.03,0.88,1.00)	0.800
Stopping & standing traffic	(0.00,0.59,1.00)	0.563
Pushing action by wheels of heavy traffic at the time of acceleration and deceleration	(0.00,0.54,1.00)	0.529
Environmental		
Differential settlement	(0.10,0.68,1.00)	0.621
Seepage of water into the subgrade	(0.00,0.64,1.00)	0.592
Seepage of water through asphalt/longitudinal joints	(0.00,0.71,1.00)	0.642
Water pooling on surface*	(0.00,0.38,0.90)	0.404
Unstable /Expansive subgrade soils	(0.10,0.84,1.00)	0.745
Natural disaster	(0.00,0.49,1.00)	0.490
Global warming	(0.00,0.73,1.00)	0.654
Trapped moisture in the bottom layers of the pavement	(0.00,0.51,1.00)	0.504
Structure		
Deterioration of aggregates	(0.00,0.84,1.00)	0.729
Ageing of binder in the surface course	(0.00,0.75,1.00)	0.667
Loss of adhesion in the surface layer	(0.00,0.63,1.00)	0.588
Structural failure of the bottom layers/movement of the bottom layers	(0.00,0.54,1.00)	0.525
Stripping on the bottom of the HMA surface layer	(0.00,0.51,1.00)	0.505
Maintenance		
Lack of supervision or supervision by unprofessional personnel	(0.00,0.53,1.00)	0.519
Insufficient funding	(0.00,0.53,1.00)	0.519
Shortage of maintenance training activities	(0.10,0.66,1.00)	0.621
Poorly maintained drains	(0.00,0.49,1.00)	0.490
Not involving local professional bodies in highway maintenance	(0.00,0.51,1.00)	0.505
End result of fatigue cracking	(0.10,0.78,1.00)	0.702

*Discarded v*alues are below the phase threshold* $(\tilde{S}-\sigma)$

Table 8: Ranked general causes of pavement distresses

Factors	Category	Sj	Rank
Design			
Underestimated traffic loads	Traffic	0.709	1
Inadequate future traffic forecast	Traffic	0.652	2
Inadequate base thickness	Structural	0.631	3
Inadequate surface drainage	Structural	0.622	4
Inadequate thickness of pavement layers	Structural	0.606	5
Poor drainability of the subbase	Structural	0.604	6
Inadequate preliminary geological investigation	Structural	0.578	7
Inadequate design knowledge	Structural	0.548	8
Construction			
Poor quality control	Construction Process	0.671	1
Use of inappropriate aggregates (hydrophilic; naturally smooth uncrushed; dusty)	Structural	0.645	2
Poor supervision and workmanship	Construction Process	0.643	3
Inadequate compaction (surface/ subbase / base)	Construction Process	0.629	4
Poor local standard of practice	Construction Process	0.557	5
Poor bond between pavement layers	Structural	0.552	6
Low binder content	Structural	0.538	7
Compaction procedure (use of conventional steel drum roller)	Construction Process	0.522	8
Poor binder to stone adhesion	Structural	0.514	9
Lifespan			
Phenomenal growth of vehicular traffic	Traffic	0.800	1
Unstable /Expansive subgrade soils	Structural	0.745	2
Deterioration of aggregates	Structural	0.729	3
Lack of control regarding load limit carried by vehicles	Traffic	0.696	4
Ageing of binder in the surface course	Structural	0.667	5
Global warming	Environmental	0.654	6
Seepage of water through asphalt/longitudinal joints	Environmental	0.642	7
Over-weight vehicles	Traffic	0.629	8
Shortage of maintenance training activities	Maintenance	0.621	9
Differential settlement	Structural	0.621	10
Seepage of water into the subgrade	Environmental	0.592	11
Lack of supervision or supervision by unprofessional personnel	Maintenance	0.519	12
Insufficient funding	Maintenance	0.519	12
High traffic volume	Traffic	0.508	14
Not involving local professional bodies in highway maintenance	Maintenance	0.505	15
Natural disaster	Environmental	0.490	16
Poorly maintained drains	Maintenance	0.490	16

Table 9: Ranked causes of deterioration for each distress

Distress	Causes		
	Design	**Construction**	**Lifespan**
Fatigue/Alligator/ Crocodile Cracking	(1) Inadequate pavement design for soil condition (0.706) (2) Inadequate surface drainage (0.622) (3) Inadequate thickness of pavement layers (0.606)	(1) Inadequate compaction (0.629)	(1) Phenomenal growth of vehicular traffic (0.800) (2)Unstable /Expansive subgrade soils (0.745) (3)Ageing of binder in the surface course (0.667) (4)Structural failure of the bottom layers/movement of the bottom layers (0.525) (5)Stripping on the bottom of the HMA surface layer (0.505)
Longitudinal/ Centre Cracking	(1)Inadequate pavement design for soil condition (0.706) (2)Weak joints between the adjoining spread of pavement layers (0.448)		(1)Unstable /Expansive subgrade soils (0.745) (2)High traffic volume (0.508) (3)Poorly maintained drains (0.490)
Transverse Cracking	(1)Inadequate pavement design for soil condition (0.706)	(1)Inadequate compaction (0.629)	(1)Unstable /Expansive subgrade soils (0.745) (2)High traffic volume (0.508)
Block Cracking	-		(1)Unstable /Expansive subgrade soils (0.745)
Meandering Cracking	-	(1)Thin asphalt layer over bridges (0.567)	(1)Differential settlement (0.621)
Rutting	(1)Inadequate pavement design for soil condition (0.706) (2)Faulty design Parameters (0.626) (3)Inadequate thickness of pavement layers (0.606) (4)Poor drainability of the subbase (0.604)	(1)Use of inappropriate aggregates (hydrophilic; naturally smooth uncrushed; dusty) (0.645) (2)Inadequate compaction (0.629) (3)Inadequate constructed surface drainage (0.571) (4)Inadequately prepared subgrade (0.550)	(1)Unstable /Expansive subgrade soils (0.745) (2)Seepage of water through longitudinal joints (0.642) (3)Over-weight vehicles (0.629) (4)Stopping & standing traffic (0.563) (5)Structural failure of the bottom layers (0.525) (6)High traffic volume (0.508) (7)Trapped moisture in the bottom layers of the pavement (0.504)
Bumps	(1)Inadequate pavement design for soil condition (0.706) (2)Inadequate surface drainage (0.622)	(1)Use of inappropriate aggregates (hydrophilic; naturally smooth uncrushed; dusty) (0.645) (2)Inadequate surface drainage (0.571)	(1)Unstable /Expansive subgrade soils (0.745)
Corrugations	(1)Lack of stability in the bitumen mix (0.522)		
Shoving	(1)Lack of stability in the bitumen mix (0.522)	(1)Use of inappropriate aggregates (hydrophilic; naturally smooth uncrushed; dusty) (0.645) (2)Poor bond between pavement layers (0.552)	(1)Unstable /Expansive subgrade soils (0.745) (2)Pushing action by wheels of heavy traffic at the time of acceleration and deceleration (0.529)
Depression	(1)Inadequate pavement design for soil condition (0.706)	(1)Inadequate compaction (surface/ subbase / base) (0.629)	(1)Movement of the bottom layers (0.525)
Potholes	(1)Inadequate pavement structure (0.622) (2)Faulty design Parameters (0.626) (3)Inadequate thickness of pavement layers (0.606)	(1)Poor bond between pavement layers (0.552) (2)Too thin bituminous surface (0.567)	(1)End result of fatigue cracking (0.702) (2)Seepage of water through asphalt/longitudinal joints (0.642) (3)High traffic volume (0.508)
Patches	-	-	-
Raveling		(1)Use of inappropriate aggregates (hydrophilic; naturally smooth uncrushed; dusty) (0.645) (2)Inadequate compaction (surface/ subbase / base) (0.629) (3)Poor binder to stone adhesion (0.514)	(1)Unstable /Expansive subgrade soils (0.745) (2)Ageing of binder in the surface course (0.667) (3)Seepage of water through longitudinal joints (0.642)
Asphalt Bleeding	-	-	-
Polishing	-		(1)High traffic volume (on an ageing pavement system) (0.508)
Delamination	(1)Inadequate surface drainage (0.622)	(1)Inadequately constructed surface drainage (0.571)	
Edge break	-		(1)Loss of adhesion in the surface layer (0.588)

Figure 1 Click here to access/download;Figure;Figure_1.pdf

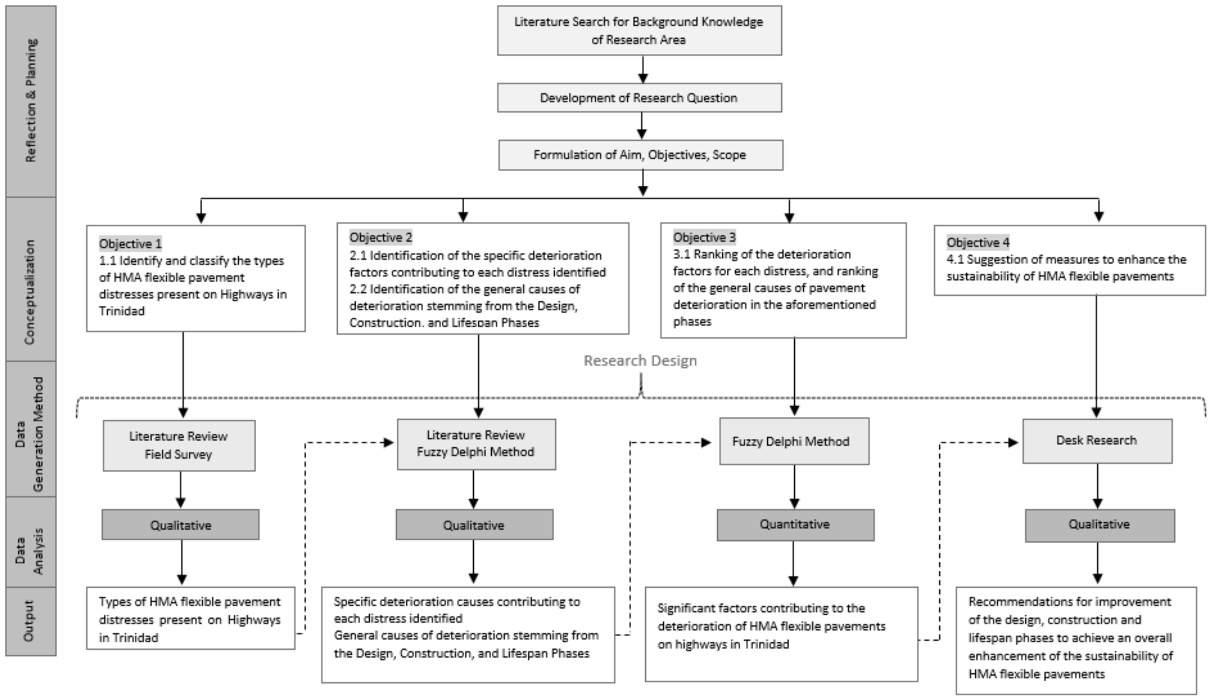

Figure 2

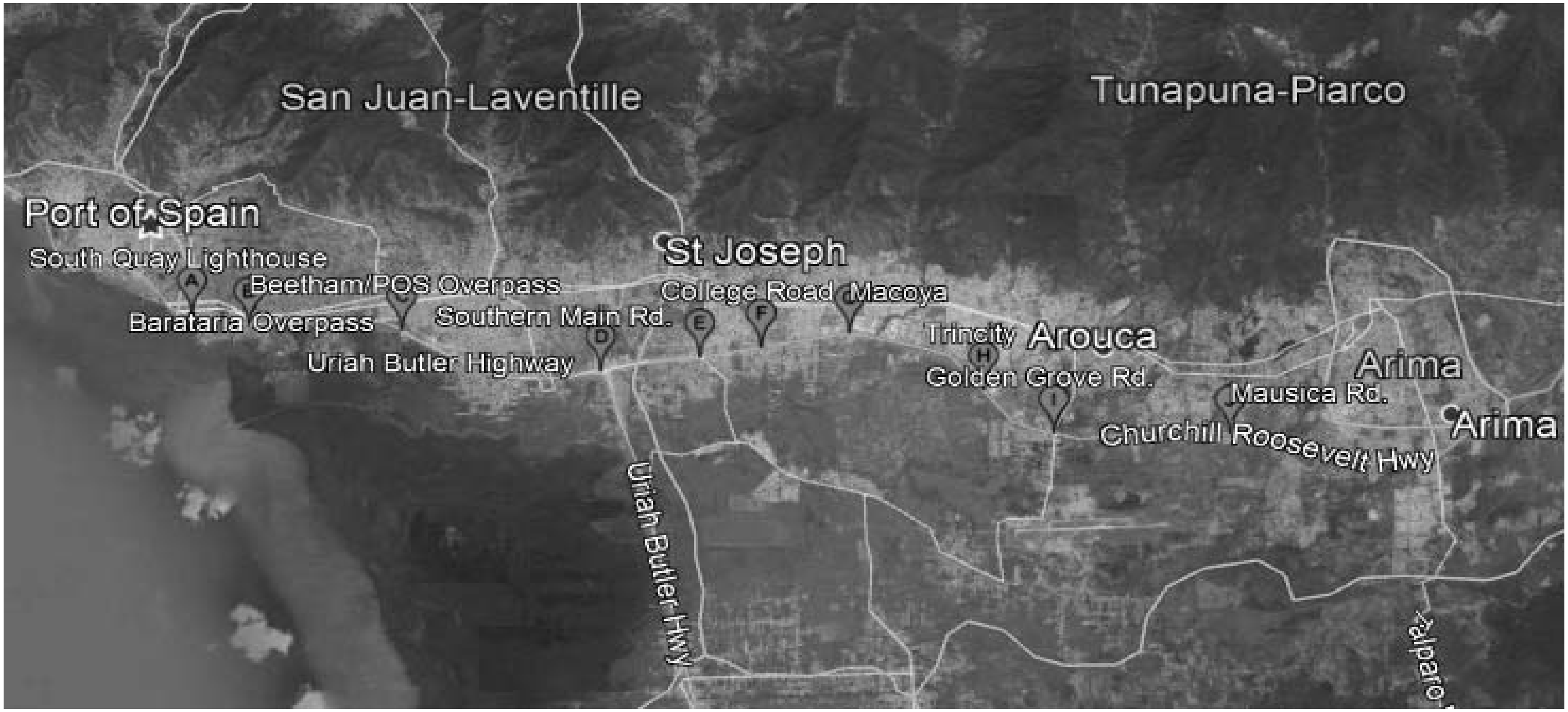
San Juan-Laventille
Tunapuna-Piarco
Port of Spain
South Quay Lighthouse
Beetham/POS Overpass
Barataria Overpass
Southern Main Rd.
Uriah Butler Highway
St Joseph
College Road
Macoya
Trincity
Arouca
Golden Grove Rd.
Arima
Mausica Rd.
Churchill Roosevelt Hwy
Arima
Uriah Butler Hwy
A
B
C
D
E
F
G
H
I
J

Figure 1: Overview of the research methodological process

Figure 2: Surveyed highways and locations of the sections (A-J)