coatings

MDPI

Article

Seasonal Signals Observed in Non-Contact Long-Term Road Texture Measurements

Vikki Edmondson [1,*], James Martin [1], Owen Ardill [2], Michael Lim [1], Malal Kane [3] and John Woodward [4]

[1] Department of Mechanical and Construction Engineering, Northumbria University, Ellison Place, Newcastle Upon Tyne NE1 8ST, UK; James.e.Martin@northumbria.ac.uk (J.M.); Michael.Lim@northumbria.ac.uk (M.L.)
[2] Highways England, Piccadilly Gate, Store Street, Manchester M1 2DW, UK; owen.ardill@highwaysengland.co.uk
[3] Campus de Nantes (ex IFSTTAR), Université Gustave Eiffel, Allée des Ponts et Chaussées, Route de Bouaye CS4, CEDEX 44344 Bouguenais, France; Malal.Kane@univ-eiffel.fr
[4] Department of Geography and Environmental Science, Northumbria University, Ellison Place, Newcastle Upon Tyne NE1 8ST, UK; John.Woodward@northumbria.ac.uk
* Correspondence: Vikki.Edmondson@northumbria.ac.uk; Tel.: +44-191-349-5930

Abstract: Texture is required on road pavements for safe vehicle braking and manoeuvres. This paper provides a unique analysis of long-term texture obtained using traffic speed condition survey (TRACS) data from 14 sites, located along a north to south transect spanning the longest highway in the UK. A total of 19 years of sensor measured texture depth (SMTD) data have been analyzed using spatial filtering techniques and compared with meteorological and traffic datasets. The results for hot rolled asphalt (HRA) surfaces reveal that changes to SMTD follow a linearly increasing trend with time. The "rate of change" is influenced by the order of magnitude of annual average daily traffic (AADT), when factored for the percentage of heavy goods vehicles. This linear trend is disrupted by environmental parameters, such as rainfall events and seasonal conditioning. In the summer, this signal is evident as a transient peak in the "rate of change" of texture greater than 0.04 mm, and in the winter as a reduction. The transient changes in texture corresponded to above average rainfall occurring in the week prior to SMTD measurement. The signal observed demonstrates an inverse pattern to the classically understood seasonal variation of skid resistance in the UK, where values are low in the summer and high in the winter. The findings demonstrate for the first time that texture measurements experience a seasonal signal, and provide compelling evidence pointing toward surface processes (such as polishing and the wetting and drying of surface contaminants) causing changes to texture that are affecting seasonal variation in skid resistance.

Keywords: pavement texture; macrotexture; skid resistance; traffic speed condition survey (TRACS); sensor measured texture depth (SMTD); friction

Citation: Edmondson, V.; Martin, J.; Ardill, O.; Lim, M.; Kane, M.; Woodward, J. Seasonal Signals Observed in Non-Contact Long-Term Road Texture Measurements. *Coatings* **2021**, *11*, 735. https://doi.org/10.3390/coatings11060735

Academic Editor: Andrea Simone

Received: 28 May 2021
Accepted: 16 June 2021
Published: 18 June 2021

1. Introduction

Road surface texture is fundamental to safe manoeuvres by vehicles on pavement surfaces [1]. Texture has previously been defined as having four increasing scales: microtexture, macrotexture, unevenness, and megatexture [2]. Microtexture and macrotexture are known to influence skid resistance, i.e., the friction available between the tire and a road surface [3–5]. Therefore, the presence of adequate pavement texture is actively monitored on highway networks by road agencies [6]. Unevenness, megatexture, and macrotexture are routinely monitored at traffic speed, using laser profile sensor techniques and cameras mounted on specialist vehicles [7]. Conversely, the frictional response to microtexture and macrotexture, whilst also surveyed at traffic speed using specialist vehicles, adopts techniques that make contact with a pavement in order to measure skid resistance. These contact techniques frequently make use of a fixed slip rate of braking test wheel [8].

Skid resistance measurements have been shown by previous researchers to be influence by a number of interrelated parameters, such as temperature, speed, presence of contaminants on the road surface, tire tread thickness and viscoelastic deformation [9,10]. A particular problem to government authorities, road agencies, asset manager, and engineers seeking to make decision on pavement surface maintenance priorities using skid resistance measurements is the phenomena of seasonal variation in skid resistance. Seasonal variation in skid resistance is the term used to describe short-term variability in skid resistance readings throughout a year [11]. Typically, skid resistance values are found to be lower in summer months and higher in winter months [8]. This phenomena of seasonal variation in skid resistance is well reported in many countries across the world [12–15], and has been recognised as an issue for eight decades [8]. Additionally, seasonal variation can lead to inter year variability in skid resistance measurement which resulted in some road agency guidance seeking to statistically adjust measurement to be in line with previous years, in order to successfully manage pavement surface assets over the longer term [6,16].

The cause of seasonal variation in skid resistance has been linked to a number of theories. One hypothesis is that skid resistance is caused by changes to surface processes [17]. In the summer months, fine dust and debris builds up on the roads, which is continually ground up under the action of tires and polishes the surface. This polishing effect is believed to lead to a smoother surface and reduced skid resistance values. Conversely, in the winter fine dust is more easily expurgated from the pavement texture, resulting in coarse debris dominating the surfaces [11]. The presence of primarily coarse debris leads to pavement surfaces becoming rougher leading to higher skid resistance readings. Another hypothesis involves the temperature of the measuring wheel making the contact measurement for skid resistance, suggesting that the tire will be stiffer during winter months leading to higher readings [18]. Alternatively, links have been suggested with meteorological conditions, with some researchers finding that friction readings are higher after periods of rainfall [19], due to the washing away of debris and contaminants from the pavement surface. Cumulative rainfall in the week preceding measurement has previously been found to be significant, with a linear trend being observed with skid resistance measurement [14]. Conversely after prolonged dry spells the same study observed a linearly decreasing trend.

The inter year deviations and seasonal variation of skid resistance has led some researchers to investigate the reliability of non-contact methods of measurement [20]. The optimisation of reliable, consistent, non-contact measurements to collect macrotexture and microtexture has been sought primarily for two reasons: (1) to model frictional skid resistance [10]; and (2) to inform maintenance decisions on where texture depth has reached a minimum threshold level requiring retexturing or pavement renewal on road networks [21,22]. The International Roughness Index (IRI) is widely used for this purpose, with acceptable IRI threshold levels specified on a country by country basis for new, reconstructed and rehabilitated roads [6]. Recent, research has also suggested that texture readings can enhance maintenance planning by estimating long-term "rates of change" from legacy data as a guide to predicting the future evolution of texture on pavement surfaces [23]. Several parameters related to vehicle type and traffic flow have been proven to have an effect on the state of texture evolution. The controlling principal is the cumulative action of loads applied by the passage of different types of vehicle across a road surface in a given time period; often expressed as equivalent standard axles [24]. Other factors relate to tire features, and tire inflation pressure which have been shown to influence the transverse application of load to a surface [25–27].

An overarching aim of the research community has been understand the correlation between frictional skid resistance and macro and microtexture measurements made in the field. Working towards this aim, recent research reported on a section of highway in

Croatia, before and after a programme of renewal, found a correlation between the level of pavement macrotexture and skid resistance [28]. Furthermore, an investigation considering 11 years of field data for a road section, found after a threshold level of cumulative traffic flow that the evolution of macrotexture increase with time whilst skid resistance decreases [13]. However, there remains a paucity of data on the potential for seasonal signals to present in macrotexture measurements. The longest study to date considered a six-year period, however this study did not consider measurements obtained in the field from an operational live highway [29]. This paper provides a unique analysis of long-term texture obtained over 19 years for 14 sites located on the A1(M); the UK's longest north to south transecting highway. Data are obtained from operational surveys using traffic speed condition survey (TRACS) measurements, as part of annual pavement monitoring undertaken by Highways England. Sensor measured texture depth (SMTD) data are analyzed using novel spatial filtering techniques and compared with meteorological and traffic data sets to produce long term evolution trends, and first compelling evidence of seasonal conditioned events in macrotexture measurements.

2. Methods

2.1. Selecting the Sites and Legacy Data

The study considers legacy raw texture depth data captured using TRACS, a purpose-built road survey vehicle [30], over a 19-year period, commencing from the 11th August 1998. The data were collected on behalf of Highways England as part of the annual maintenance survey of the UK Strategic Road Network (SRA) [31]. The TRACS vehicle was calibrated in accordance with the UK Standard [30], to safeguard the quality of data during the stages of data collection, storage, and post processing. The TRACS texture data were obtained at a traffic speed of 50 km/h using laser triangulating profile sensors [32]. The texture data were measured by TRACS in a 300 mm wide swath, positioned over the nearside wheel track of the lane being surveyed. The vehicle has inertia-corrected global positioning system (GPS) data in conjunction with distance measurement, to reference the location of a texture reading to a longitudinal accuracy of ±1m. Texture data were obtained for 14 sites located on the A1(M). At 659.8 km it is the longest north to south highway in the UK, connecting Edinburgh with London. Study sites were selected where long-term (typically >12 years) legacy data were available for the same surface material. Hot rolled asphalt (HRA) surfaces were selected as they have been used widely on the SRA and thereby provide the largest, longest, and most representative dataset. HRA is a type of hot mix asphalt often used in the United Kingdom. It is a dense gap graded asphalt of mineral aggregate, sand, filler, and typically a 40/60 penetration bitumen binder. There is a high proportion of sand in the mix resulting in a low percentage of air voids when it is compacted. High polished stone value bitumen coated 20 mm aggregate are rolled into the surface of the mixture after laying to provide a skid resistance surface [33].

Sites with HRA were selected for comparison in the North and South of England, to allow the greatest potential differences in traffic flow and meteorological conditions for study purposes. Sites were also selected at locations with traffic counters. A total of 10 suitable sites were identified in the North of England, located at approximately 20 km intervals (refer to Figure 1a) and four in the South of England (refer to Figure 1b). Fewer sites were available in the South due to frequent resurfacing, disrupting the availability of consistent long-term records for a single surface material.

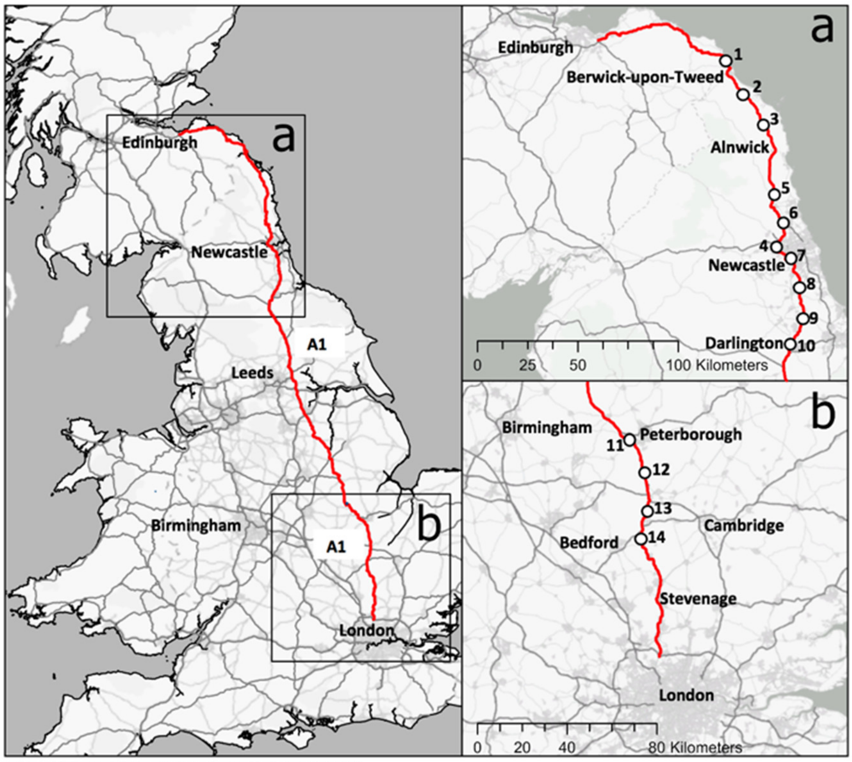

Figure 1. Location of the study sites on the A1 in the United Kingdom. (**a**) the northern sites (**b**) the southern sites.

The A1(M) varies along its route from one to four lanes. Data for the sites were collected from the inside lane of the southbound side of the A1(M). The southbound inside lane was considered more likely to have the heaviest traffic usage being the lane favoured by heavy goods vehicles (HGV). The mean average length of the inside southbound lane considered at each site was 800 m. The raw texture depth data captured by TRACS for these sites were preprocessed by the Highway Agency's machine preprocessor and stored as SMTD in the Highways Agency Pavement Management System (HAPMS) [30], for a 300 mm evaluation length at 10 m intervals, as previously described in [23]. SMTD is used in the UK for texture reporting and has previously been found to relate to mean profile depth (MPD) by the relationship [34]:

$$MPD = 1.4 \times SMTD^{0.840}, \tag{1}$$

2.2. Data Processing of the SMTD Data

Once extracted from HAPMS, a 0.1 m^{-1} low pass wavenumber filter [35] was then applied to the SMTD using mathematical programming software [36] at each 10m interval to remove high wavenumber (short wavelength) noise from the longitudinal road texture signal. The mean SMTD data over the overall lane chainage considered at each TRACS epoch were then calculated and plotted for each site to show the long-term evolution of SMTD through time. The mean bias of the 5th epoch data point for each site was then calculated and removed from the filtered mean SMTD to normalise the data.

2.3. Comparison of SMTD with Traffic Flow

The rate of change in SMTD data was compared with both annual average daily traffic (AADT) flows and HGV AADT flows; and linear best fit lines added to the plotted data. To determine the variability in these data, the rate of change was characterised both for the full time period of SMTD measurement available at an individual site, and for the linear trend occurring between the pronounced "troughs" at point (I) and (II) on Figure 2 for the northern sites and point (I) and (II) on Figure 3 for the southern sites.

A decadal AADT was calculated from WebTRIS Highways England Traffic [37] flow data, to differentiate the traffic flow usage at the different sites on the A1(M). The data were collected using a series of fixed induction loop road sensors. The AADT flows were calculated from the latest available data (from 1 January 2010 to 31 December 2019), there was no significant fluctuation in AADT flows over this period at individual sites. Finally, the AADT flows were factored by the mean percentage of HGVs, calculated from the annual HGV percentage figures for the same period.

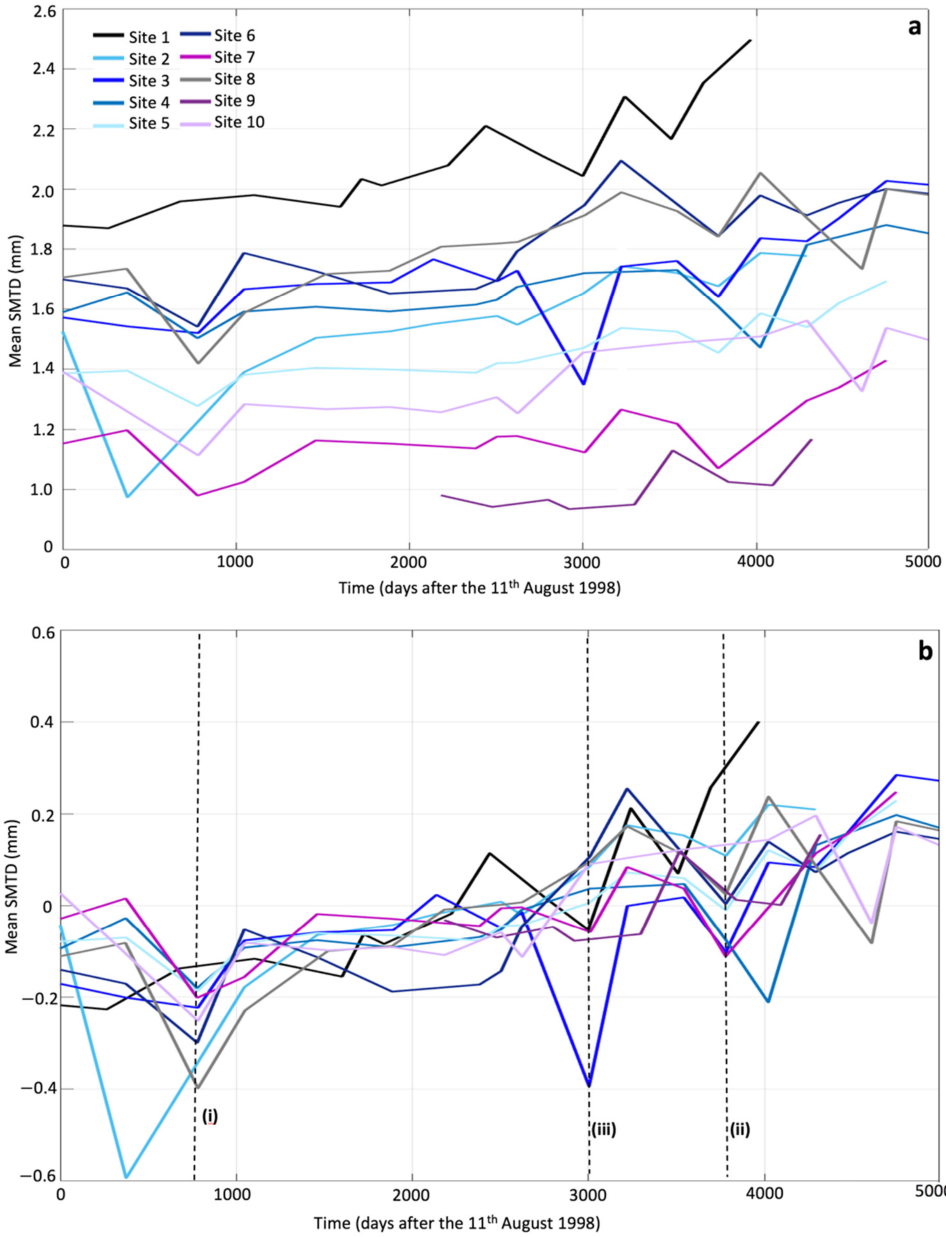

Figure 2. (**a**) Filtered mean sensor measured texture depth (SMTD) data for the northern sites on the A1. (**b**) Normalised mean SMTD data for the northern sites on the A1. (I) to (III) are "troughs" in data coinciding with severe rainfall events. (see text for further explanation).

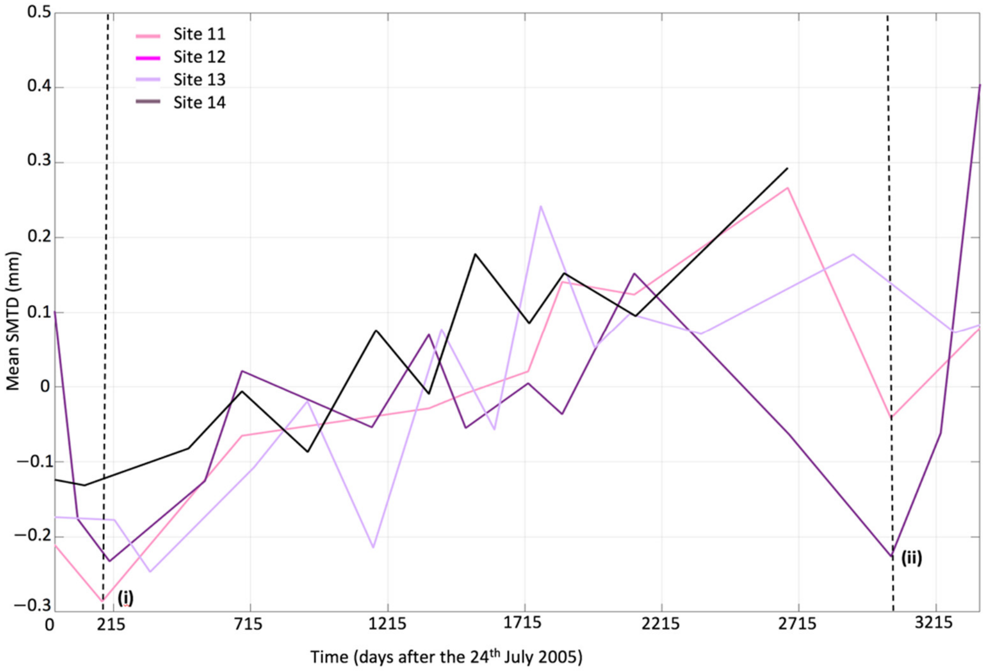

Figure 3. Normalised mean sensor measured texture depth (SMTD) data for the southern sites on the A1. (I) and (II) are "troughs" in data coinciding with severe rainfall events. (See text for further explanation).

2.4. Seasonal Analysis

A 7th order polynomial best fit line was applied to the filtered mean SMTD for each site to model the long-term trends of texture evolution. Lower order polynomials were tested, but the 7th order was found by observation to best represent the evolution of mean SMTD for sites. The deviations of mean SMTD from the long-term trends were then characterised. "Troughs" were defined as negative deviations and "peaks" positive deviations greater than 0.04 mm. Deviations less than 0.04 mm represent very minor fluctuations from the trend and were not considered significant. The sequencing of the "peaks" and "troughs" within a year, where plotted as a day number against the magnitude of the deviation to characterise the seasonality of the deviations. Finally, the timings of the "peaks" and "troughs" where compared with rainfall records.

Daily rainfall records were obtained from the UK Meteorological (Met) Office (2019) MIDA UK Hourly Rainfall Data [38] for the precipitation gauge nearest to each of the A1(M) sites. The rainfall data were totalled for each month and subtracted from the monthly mean for the overall study period for the northern and southern sites, respectively. The resultant change in monthly rainfall from the monthly mean for the overall study period, was plotted on the same graph as the "peak" and "trough" deviations of mean SMTD from the long-term trend. Furthermore, the graphical markers for the "peaks" and "troughs" were scaled to represent the magnitude of cumulative rainfall seven days prior to the date of the SMTD measurement by TRACS.

3. Results

3.1. Changes in Road Texture

The filtered mean SMTD data for the A1(M) northern sites are shown on Figure 2. SMTD data for nine sites (Sites 1 to 8 inclusive and Site 10) were first measured on either the 11 or 12 August 1998. The initial mean SMTD measurements vary on Figure 2a for these sites, from 1.18 mm to 1.88 mm. The construction records available of Sites 1 to 8 indicated that these HRA pavement surfaces were first constructed between 1976 and 1993, so the youngest pavements had been laid for a minimum of five years when they were first measured. No clear correlation was found between the dates of construction and the initial measurement of SMTD recorded on August 1998. This suggests that the evolution of pavement SMTD is influenced by site specific processes, such as meterological conditions and traffic flow.

The normalised data are shown in Figure 2b. For the period on the graph between 1000 days and 3500 days after the 11 August 1998, the filtered mean SMTD generally increases linearly with the passage of time for all the northern sites (sites 1 to 10). A similar trend is demonstrated in the normalised filtered mean SMTD data for the four southern sites 11 to 14, shown on Figure 3. The period on the graph between 215 and 2215 days after the 24 July 2004 again shows that the data like the north follows a general linear trend increasing with time. The rate of change of SMTD is steeper for southern sites (sites 11 to 14) than for the northern sites (sites 1 to 10). The collective rate of change in the filtered mean SMTD was 2.017×10^{-4} mm/day for the northern sites (site 1 to 10) between 1000 and 3500 days after the 11 August 1998, and 8.459×10^{-5} mm/day for the southern sites (sites 11 to 14) between 215 and 2415 days after 24 July 2005, representing a difference of 238%. The southern sites (sites 11 to 14), with closer proximity to London experience much higher volumes of traffic, than the northern sites (sites 1 to 10). The mean AADT flow for the collective group of southern sites is 30070 vehicles, compared to 11645 vehicles for the collective group of northern sites. The difference between the collective group of southern and northern sites is 258%, a comparable magnitude to the difference in gradient of the rate of change in filtered SMTD. Thus, suggesting that SMTD change may be influenced amongst other factors by traffic flow.

The rate of change in filtered mean SMTD compared with AADT is shown in Figure 4a, for the individual sites analyzed. As AADT increases then the HRA pavement surfaces are experiencing a greater rate of change in SMTD. The same is also true when AADT figures are factored to take into account the mean percentage of HGVs. Figure 4b shows a positive trend between the rate of change in the filtered mean SMTD and the HGV AADT flow. Interestingly, the gradient of the linear best fit line on Figure 4a at 4.44×10^{-9} mm/AADT is 20% as steep as the linear best fit line for the adjusted HGV AADT values at 2.23×10^{-8} mm/AADT shown on Figure 4b. This suggests that HGVs are having more impact on the evolution of mean SMTD than other vehicles. This result meets expectation as HGVs have previously been attributed as the main cause of change on pavement surfaces due to heavier axle loading and tire features [24,25,27].

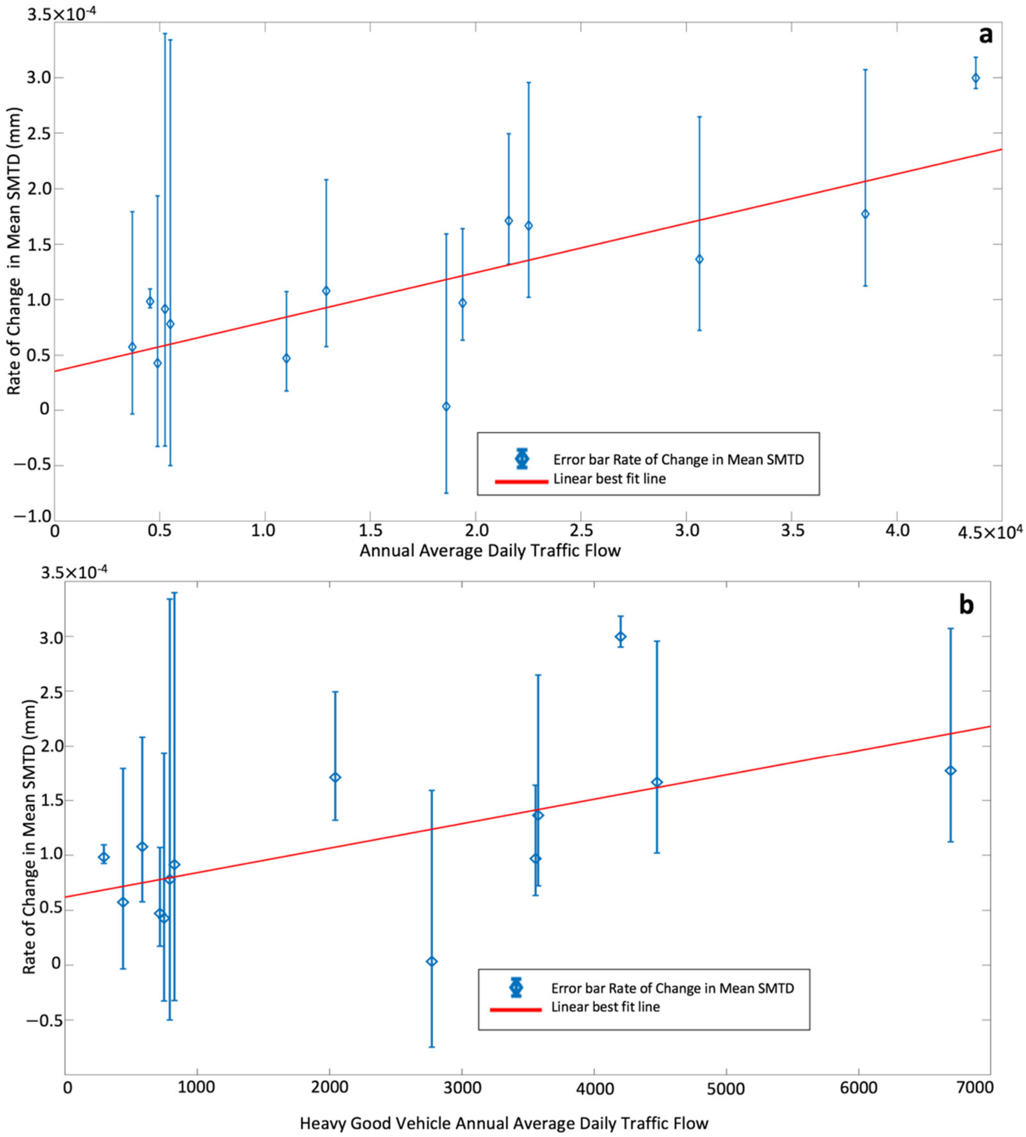

Figure 4. (**a**) Rate of change in mean sensor measured texture depth (SMTD) data compared with annual average daily traffic flow (AADT). (**b**) Rate of change in SMTD compared with heavy goods vehicle (HGV) AADT.

3.2. Seasonal Trends in Road Texture

The general linear trend in the normalised filtered mean SMTD is interrupted on Figure 2b at (I), (II), and (III), with a drop or "trough" occurring of approximately 0.2 mm. When these time series were investigated it was found they coincided with periods of intense precipitation. Point (I) for example occurs in autumn 2000, at the time the wettest recorded since 1766 on the England and Wales Precipitation Series [39] experiencing 503 mm of precipitation, which was 196% of the 1961 to 1990 autumn average. Similar behaviour was observed for the southern sites, for example point (II) on Figure 3 shows a drop or "trough" in the mean filtered SMTD data, on the 30 November 2013. The winter of 2013 was again exceptionally wet, at the time the third wettest since 1766 [39], with Central and Southern England experiencing 250% of the 1981 to 2010 winter average. The general linear evolution of filtered mean SMTD for the HRA surfaces studied was found to be repeatedly disrupted by extreme precipitation events. Other meteorological triggers were investigated including ground surface temperature, minimum and maximum ambient temperature, and number of frost days, but no clear correlation with the transient drop or "troughs" in the mean SMTD was established.

A detailed study was made of the "peaks" and "troughs" occurring in the filtered mean SMTD data for each of the sites, within the northern and southern groups. It was found that the long-term trends in filtered mean SMTD against time in days could be modelled as a 7th order polynomial for all the sites. The 7th order polynomial was found to represent the long-term trend, from which the "peaks" and "troughs" can be detected. Figure 5 shows as an example, the 7th order polynomial best fit line for Site 3 (one of the northern sites, Figure 1a) as a black dashed line and the filtered mean SMTD as a red line. The deviations in filtered mean SMTD from the 7th order polynomial trend are presented as red crosses for "troughs" and blue crosses for "peaks", for negative and positive deviations greater than 0.04 mm, respectively. Deviations less than ±0.04 mm are not considered significant (presented as green crosses in Figure 5). The same order polynomial arising for all the sites modelled, indicates that the rate of change in filtered mean SMTD with time follows a trend, and the trend is influenced by site specific conditions as the polynomial is a of a higher order.

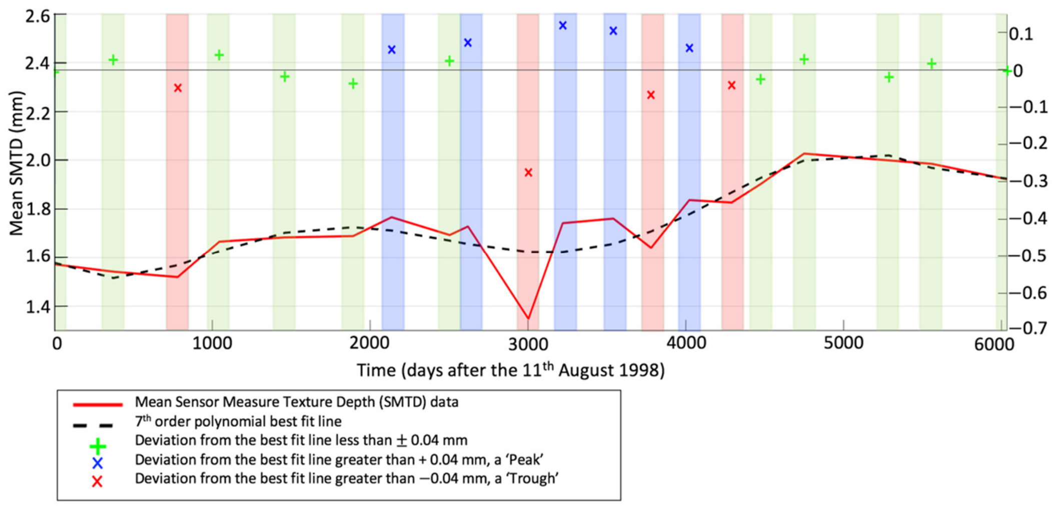

Figure 5. Mean sensor measured texture depth (SMTD) data compared with a 7th order polynomial best fit line for Site 3 on the A1.

The timing of the "peak" and "trough" deviations from the filtered mean SMTD for the northern sites are plotted according to seasonal periods in Figure 6. It was found that the "peaks" shown as blue circles on the Figure 6, generally occur in the summer period characterised as the 1 April through to the 30 September. Conversely "troughs" shown as red diamonds in Figure 6, generally occur in the winter period, characterised as the 1st October to the 31 March. The clustering in Figure 6 indicates a seasonal signal in the deviations in filtered mean SMTD data from the long-term trends. Moreover, the surface processes governing this signal is likely to vary from the summer to the winter period, as clear contrasting patterns are discernable in the data.

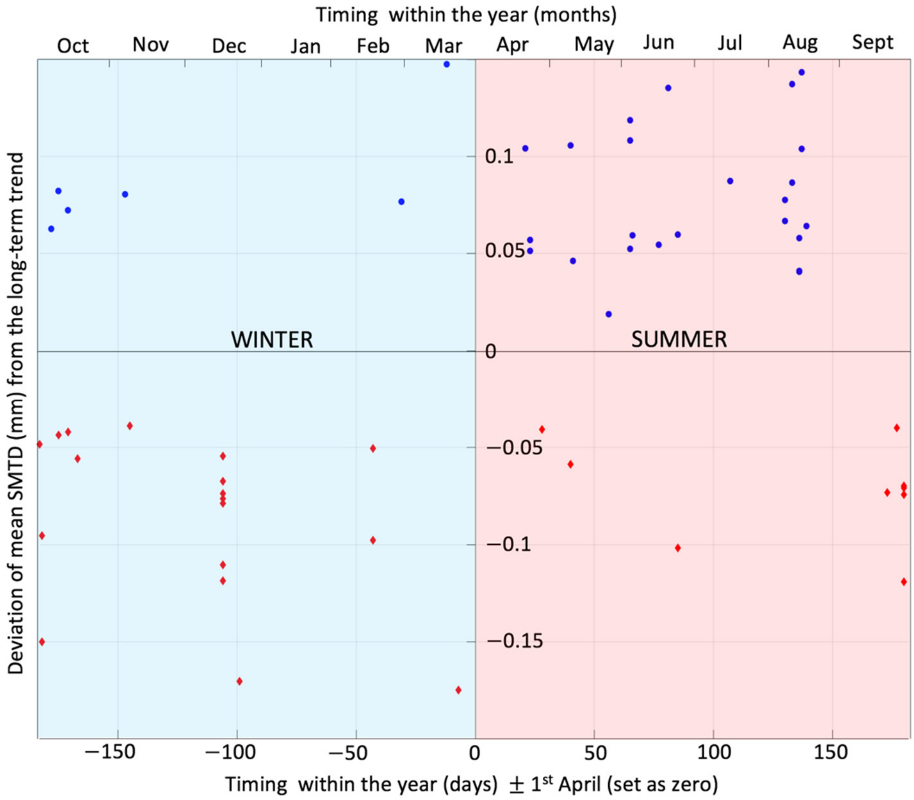

Figure 6. The graph plots the seasonal timing of the deviation in "peaks" and "troughs" from the 7th order polynomial trend for the northern sites of the A1.

The surface processes with the potential to contribute to the seasonal signal are examined in the discussion section of this paper. These processes dominate when above average precipitation occurs close to (within 7 days of) the collection dates for the SMTD data. Figures 7 and 8 plot for the northern and southern sites, respectively, the "peaks" and "troughs" in filtered mean SMTD against the preceding (seven days) rainfall. The blue shaded bands on the plots represent the winter months of October to March and the change in monthly rainfall from the mean over the study period (August 1999–July 2016) are provided for context. The seasonal bias in the positioning of the peaks and troughs is evident, with the negative deviation ("troughs") from the filtered mean long-term SMTD trend predominantly occurring in the winter months, and the short-term positive deviations ("peaks") occurring in the summer months.

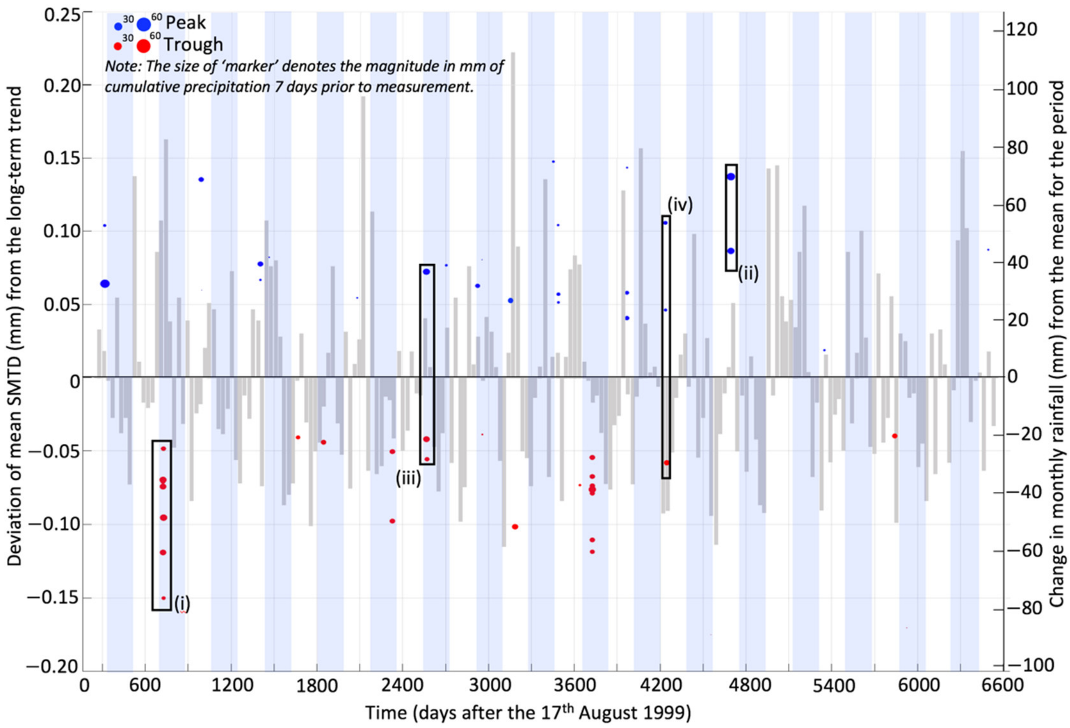

Figure 7. The graph plots change from mean monthly rainfall for the period 17 August 1999 to 17 July 2016, against the "peaks" and "troughs" in the deviation of mean SMTD for the northern sites on the A1. (See text for full explanation).

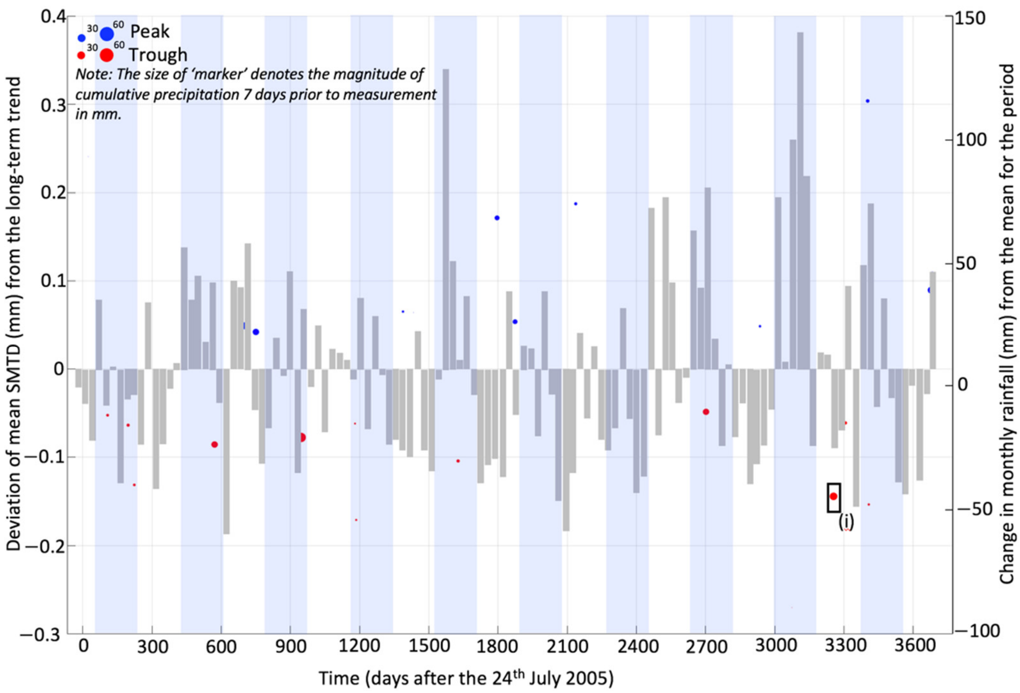

Figure 8. The graph plots change from mean monthly rainfall for the period 24 July 2005 to 1 August 2015, against the "peaks" and "troughs" in the deviation of mean SMTD for the southern sites on the A1. (See text for full explanation).

There is evidence of "troughs" or "peaks" occurring at multiple sites at similar times (see for example Figure 7 (I) and (II)). On Figure 7 at point (I), "troughs" in the signal were observed at six independent sites (Sites 2, 4, 5, 6, 7, and 10) over five days between 28 September 2000 and 2 October 2000. These sites are located at intervals of approximately 20 km over a 154 km stretch of the A1(M). This consistency across multiple sites is occasionally complicated by the close occurrence of "peaks" and "troughs" at different sites. On Figure 7 at point (III), one "peak" and two "troughs" occur in October 2005, a winter period. Furthermore, at point (IV) on Figure 7 two "peaks" and one "trough" occur in the summer period of May 2010. Upon investigation the "peaks" and "troughs" for both time series considered occurred within five days of two days of heavy precipitation. These data suggest a bias towards the observed seasonal pattern (with more "peaks" occurring in the summer, and more "troughs" in the winter), and points also to the potential for site-specific responses potentially influenced by interruptive events, such as the presence of a surface covering of mud. The hypothesis that precipitation is occasionally a trigger for transient change in SMTD data with local road surface conditions governing, is reinforced by the data presented in Figure 8 (see point (I)), where a "trough" occurs on the 30 May 2014 early within the summer period for a southern site. The winter of 2013/2014 was recorded as being particularly wet across south-east England, being at the time the wettest since 1766 [40]. In the month of May 2014, 83.5 mm of precipitation fell. In the week prior to the SMTD reading being taken on the 30 May 2021, 57% or 47.6 mm of this precipitation was recorded. This intense period of precipitation occurred after a dry spell of seven days. The data indicate that "peaks" and "troughs" occur where there has been above average precipitation for several days within the week prior to a measurement being taken, suggesting that processes occurring on the HRA pavement surface are temporarily interrupted by surface processes such as precipitation. Furthermore "peaks" and "troughs" generally present with a seasonal signal, potentially conditioned by local, site specific controls.

4. Discussion

To summarise the trends observed in data from the study results and to advocate the surface processes that might be driving these we present Figure 9 our conceptual model. The governing trends of long-term change to texture on HRA pavement surfaces is shown as thick black line on Figure 9, at an angle of (∅). This illustrated that uninfluenced by exceptionally high precipitation, the rate of change in filtered mean SMTD was found to continue to increase linearly with time, at a gradient (∅) that was correlated with the magnitude of AADT for the sites considered. Furthermore, the observed steepening of the angle (∅) when AADT is adjusted for the percentage of HGVs is expected because the heavier axle loading and tire types associated with commercial vehicles cause more impact on macrotexture polishing than other types of road vehicles [24–26]. These observed long-term linearly increasing trends do not consider the very "early life" of the HRA pavement (represented on Figure 9 conceptually as a grey hatched vertical band), a period likely to be governed by other processes, such as the stripping of bitumen bloomed on a newly laid surface [41].

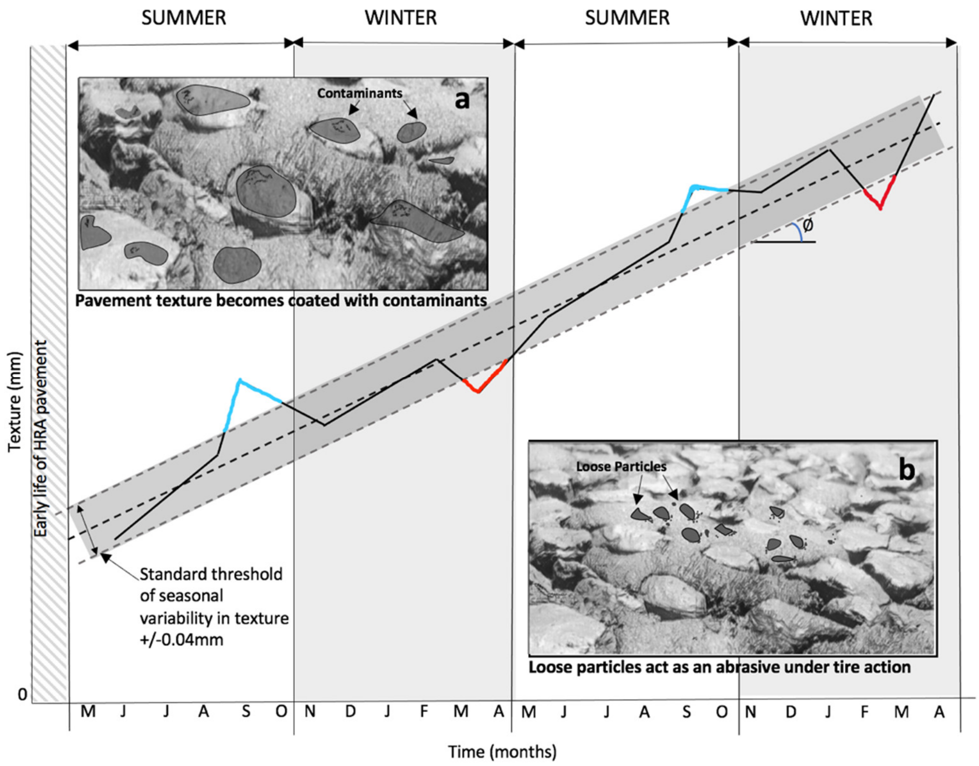

Figure 9. The governing trends of long-term change to pavement texture on hot rolled asphalt (HRA) pavement surface. (**a**) During the summer season pavement texture can become coated with contaminants such as the residue of rubber or rubber particles from vehicle tires, oils or auto lubricants. (**b**) During the winter season frost shattering in pavement microcracks, leads to loose particles, which can act as an abrasive under tires, polishing the pavement surface.

The presentation on the conceptual model (refer to Figure 9) of a long-term increase in filtered mean SMTD data with time, at a gradient (Ø) correlated with AADT, is a finding aligned with other studies. Pomoni et al. [13] tracked change on a hot mix asphalt surface using cumulative traffic data and observed an increase in macrotexture on pavement surfaces after a threshold level of cumulative traffic had been achieved in the life of the pavement. Prior to the threshold, during the early life of the pavement the change in surface texture was shown to behave differently. Generally, Pomoni et al. [13] observed a decreasing trend with some fluctuations in texture results attributed to short-term variations arising from changes in the asphalt surface due to processes influenced by conditions of the area, for example the influence of dust and rain.

Similar minor annual variability was found in the long-term data considered during this study, characterised as change in filtered mean SMTD values less than ±0.04 mm. These are presented on the conceptual model (Figure 9) as the area within the linear grey band. Changes less than 0.04 mm in SMTD are thought to represent surface processes occurring in the winter and summer. Previous researchers have presented hypotheses over these governing processes, the most plausible from the results studied are again presented conceptually on Figure 9. Box (a) on Figure 9 illustrates that in the summer pavement texture can becomes coated with residual rubber, rubber particles, oils, and lubricants [8,42]. Furthermore, sunny days with air temperatures of 20 °C or above can generate road surface temperatures of the order of 50 °C as dark asphalt surfaces absorb heat. This has been shown to be sufficient to cause unmodified binders present in a road to become sticky in places with the potential to smut and cover part of the pavement surface in localised areas [43].

Box (b) on Figure 9 illustrated that in the winter at temperatures below 0 °C water present in small voids in the pavement aggregate can freeze. The resulting 9% volumetric expansion in this water can cause fragments of aggregate to break away from the pavement surface, a process known as frost shattering. This can lead to loose aggregate on the pavement surface, which can act as an abrasive under tires polishing the pavement surface [11]. The potential for voids is increased by embrittlement in asphalt pavements caused by the aging of the saturate, aromatic, resin, and asphaltene (SARA) components of the bitumen binder through oxidisation under ultra-violet radiation and hydrological erosion [44]. Embrittlement of the binder leads to the development of micro-cracks into which water can infiltrate and freeze. These theoretical seasonal surface phenomena are widely accepted, but much research is still required to monitor them practically in the field.

It is discernable from the results of the study undertaken that whilst within the threshold of ±0.04 mm these surface processes are "in balance". However, disruptions are observed arising from notable precipitation events, causing the development of "peaks" in the deviation of filtered mean SMTD from long term trends during summer months and "troughs" in the winter months. Figure 9 illustrates the "peaks" occurring in the summer as blue shading on the black texture evolution line, and similarly the "troughs" occurring in the winter as red shading.

The link between above average precipitation events and transient changes in SMTD suggests that a washing effect may be occurring on the HRA pavement surface. In the summer months the disruptive precipitation events are potentially removing any oil, lubricants, rubber, or rubber particle contaminants present either on the surface of the HRA aggregate or within the voids, causing an increase in the SMTD measurements. In the summer, these contaminants are likely to be drier and, therefore, more likely to be expelled from the pavement macrotexture in an emulsion. In the winter, it its theorised that due to the quantity of abrasive material and also sand from road salting activities present on the surface, that polishing of the HRA aggregate governs. It has been suggested by other researchers that whether a surface becomes more polished or whether it becomes rougher is a function of the minerology and polish stone values of the aggregate and of the nature of dust/detritus finding its way onto the pavement surface [8]. However, it is clear from the data presented here that negative deviations from filtered mean SMTD from the long-term trend are typically occurring after above average precipitation in the winter. It is, therefore, postulated that either dust, debris, and sand from salting on the surface are being "redistributed" within the negative texture of the HRA pavement; or that the contaminants in the winter are more likely to be miscible on the surface and less susceptible to washing. Ultimately, little is known about the characteristics of precipitation needed to effectively clear or clean a highway surface or the wetting and drying processes occurring and interacting with surface contaminants [8].

It is clear that rainfall is acting to disrupt the SMTD. The findings presented here demonstrate for the first time that the disruption has a seasonal pattern. Interestingly this pattern follows an inverse trend to the classically understood pattern of seasonal variation in skid resistance in the UK, where skid resistance is thought to be lower in the summer and higher in the winter. As skid resistance is measured as a frictional response to pavement texture, this suggests that processes on pavement surfaces are influencing seasonal variation in skid resistance; along with the other recognised parameters such as speed, temperature, tire tread thickness, and viscoelastic deformation. An inverse relationship between texture and skid resistance has been observed by others [13] when considering the long-term pavement texture evolution with cumulative traffic. Furthermore, recent studies seeking to determine a percentile dry skid resistance based on wet period measurement, noticed the same percentile occurring with different traffic and precipitation intensity, concluding that this pointed to the potential for asphalt pavement surfaces to be influencing seasonal variation [13]. Certainly, the summer "peak" signals were observed during the months of April to September, which broadly match the seasonal summer period of low skid resistance measurement in the UK [16]. Further study of the seasonal signal observed in the SMTD will be required to ascertain the contribution of surface processes to seasonal variations of skid resistance. Such research will require measuring in a controlled manner: skid resistance, macrotexture depth, environmental conditions, and monitoring at the macroscale the wetting and drying processes of contaminants on the surface of the pavement. These findings demonstrate that texture measurements experience a seasonal signal and point to a requirement for measuring equipment to be modified to clean pavement surface of detritus prior to readings being taken to achieve more accurate and representative measurement of SMTD.

5. Conclusions

An investigation of the long-term evolution of SMTD for HRA surfaces was undertaken for 14 sites located on the north to south transect of the A1(M) in the UK and compared with traffic flow and metrological dataset for 19 years. Sensor measured texture depth (SMTD) data were analyzed using novel spatial filtering techniques. The long-term evolution of SMTD for HRA surfaces, when seasonal signals are discounted in the "rate of change", follow a linearly increasing trend at a gradient ($\emptyset$) correlated to the order of magnitude of the AADT. The results also demonstrate for the first time a seasonal signal in SMTD measurements corresponding with above average precipitation occurring within the week prior to the SMTD measurement being taken. The pattern observed demonstrates positive deviation from the long-term evolution of filtered mean SMTD in the summer and negative deviations in the winter. The results indicated that processes occurring on the surface of the HRA pavement are influenced by seasonal conditioning.

The study results are presented as a new conceptual model summarising the governing trends of long-term change on hot rolled asphalt pavement surfaces. The conceptual model considers new theories of the surface processes driving the detected patterns related to the wetting and drying of surface contaminants. In the summer, the build-up of surface contaminants (such as rubber, rubber particles, oils, and lubricants) are likely to be drier and are believed to be washed away with rainfall more easily from the pavement texture in an emulsion. In the winter, it is postulated that either dust, debris, and sand from salting on the surface are being "redistributed" within the negative texture of the HRA pavement; or that the contaminants in the winter are more likely to be miscible on the surface and less susceptible to washing. The pattern observed is inverse to the behaviour of seasonal variation in skid resistance because skid resistance is measured as a friction response to texture. However, further research is required to confirm conclusively the link between the two phenomena. Such research will require measuring in a controlled manner: skid resistance, macrotexture depth, environmental conditions, and monitoring at the macroscale throughout the wetting and drying processes of contaminants on the surface of the pavement.

The results presented suggest that more accurate reading of pavement texture might be obtained by cleaning the surface of debris/contaminant prior to measurement being performed. Although this may not be practical at road network scale, more frequent texture surveys synergised with more focused and constrained weather monitoring will do much to improve the understanding of surface processes on the evolution of texture.

Author Contributions: Conceptualisation, V.E., J.M., M.L., and J.W.; methodology, V.E. and J.M.; software, V.E. and J.M.; validation, V.E., J.M., and M.L.; formal analysis, V.E., J.M., M.L., and J.W.; investigation, V.E. and M.L.; resources, O.A.; data curation, V.E. and M.L.; writing—original draft preparation, V.E.; writing—review and editing, V.E., J.M., M.L., M.K., and J.W.; visualisation, V.E. and J.W.; supervision, M.L., M.K, O.A., J.M., and J.W.; project administration, V.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Traffic data can be obtained at [37] and precipitation data at [38]. The SMTD data are not publicly available.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Meegoda, J.N.; Gao, S. Evaluation of pavement skid resistance using high speed texture measurement. *J. Traffic Transp. Eng. Engl. Ed.* **2015**, *2*, 382–390, doi:10.1016/j.jtte.2015.09.001.
2. ISO 13473-1:2019. Characterization of Pavement Texture by Use of Surface Profiles—Part 1: Determination of Mean Profile Depth. Available online: https://www.iso.org/obp/ui/#iso:std:iso:13473:-1:ed-2:v1:en (accessed on 27 May 2021).
3. Klüppel, M.; Heinrich, G. Rubber friction on self-affine road tracks. *Rubber Chem. Technol.* **2000**, *73*, 578–606, doi:10.5254/1.3547607.
4. Persson, B.N.J. *Sliding Friction: Physical Principles and Applications*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2013.
5. Moore, D.F. THE Friction of Pneumatic Tyres. 1975. Available online: https://trid.trb.org/view/1058308 (accessed on 27 May 2021).
6. Múčka, P. International roughness index specifications around the world. *Road Mater. Pavement Des.* **2017**, *18*, 929–965, doi:10.1080/14680629.2016.1197144.
7. Peraka, N.S.P.; Biligiri, K.P. Pavement asset management systems and technologies: A review. *Autom. Constr.* **2020**, *119*, 103336, doi:10.1016/j.autcon.2020.103336.
8. Kogbara, R.B.; Masad, E.A.; Kassem, E.; Scarpas, A.; Anupam, K. A state-of-the-art review of parameters influencing measurement and modeling of skid resistance of asphalt pavements. *Constr. Build. Mater.* **2016**, *114*, 602–617, doi:10.1016/j.conbuildmat.2016.04.002.
9. Kane, M.; Edmondson, V. Tire/road friction prediction: introduction a simplified numerical tool based on contact modelling. *Veh. Syst. Dyn.* **2020**, 1–20, doi:10.1080/00423114.2020.1832696.
10. Kane, M.; Edmondson, V. Modelling the bitumen scour effect: Enhancement of a dynamic friction model to predict the skid resistance of rubber upon asphalt pavement surfaces subjected to wear by traffic polishing. *Wear* **2018**, *400–401*, 100–110, doi:10.1016/j.wear.2017.12.013.
11. Wilson, D.J. The Effect of Rainfall and Contaminants on Road Pavement Skid Resistance, no. 515. 2013. Available online: https://trid.trb.org/view/1250850 (accessed on 28 May 2021).
12. Jayawickrama, P.W.; Thomas, B. Correction of field skid measurements for seasonal variations in texas. *Transp. Res. Rec. J. Transp. Res. Board* **1998**, *1639*, 147–154, doi:10.3141/1639-16.
13. Pomoni, M.; Plati, C.; Loizos, A.; Yannis, G. Investigation of pavement skid resistance and macrotexture on a long-term basis, *Int. J. Pavement Eng.* **2020**, 1–10, doi:10.1080/10298436.2020.1788029.
14. Bijsterveld, W.; del Val, M.A. Towards quantification of seasonal variations in skid resistance measurements. *Road Mater. Pavement Des.* **2016**, *17*, 477–486, doi:10.1080/14680629.2015.1090909.
15. Oh, S.M.; Madanat, S.M.; Ragland, D.R.; Chan, C.-Y. Evaluation of Traffic and Environment Effects on Skid Resistance in California. 2010, p. 12. Available online: https://escholarship.org/uc/item/01p1d923 (accessed on 17th June 2021).
16. CS 228-Skidding Resistance-DMRB. Available online: https://www.standardsforhighways.co.uk/dmrb/search/50d43081-9726-41e8-9835-9cd55760ad9e (accessed on 28 May 2021).
17. Ahammed, M.A.; Tighe, S.L. Early-life, long-term, and seasonal variations in skid resistance in flexible and rigid pavements. *Transp. Res. Rec. J. Transp. Res. Board* **2009**, *2094*, 112–120, doi:10.3141/2094-12.
18. Kennedy, C.K.; Young, A.E.; Butler, I.C. Measurement of Skidding Resistance and Surface Texture and the Use of Results in the United Kingdom. In *Surface Characteristics of Roadways: International Research and Technologies*; ASTM International: West Conshohocken, PA, USA, 1990; p. 87, doi:10.1520/STP23355S.
19. Henry, J.J. *Evaluation of Pavement Friction Characteristics*; Transportation Research Board: Washington, DC, USA, 2000.
20. Edmondson, V.; Woodward, J.; Lim, M.; Kane, M.; Martin, J.; Shyha, I. Improved non-contact 3D field and processing techniques to achieve macrotexture characterisation of pavements, *Constr. Build. Mater.* **2019**, *227*, 116693, doi:10.1016/j.conbuildmat.2019.116693.
21. CS 229-Data for pavement assessment-DMRB. Available online: https://www.standardsforhighways.co.uk/dmrb/search/2e9e1b1c-528a-4b7d-bea8-d1c49a3caded (accessed on 28 May 2021).
22. Abbondati, F.; Biancardo, S.A.; Veropalumbo, R.; DellAcqua, G. Surface monitoring of road pavements using mobile crowdsensing technology. *Measurement* **2021**, *171*, 1–11, doi:10.1016/measurement.2020.108763.
23. Edmondson, V.; Ardill, O.; Martin, J.; Lim, M.; Kane, M.; Woodward, J. Quantifying long-term rates of texture change on road networks. *Int. J. Pavement Eng.* **2020**, 1–13, doi:10.1080/10298436.2020.1830283.
24. Bagui, S.; Das, A.; Bapanapalli, C. Controlling vehicle overloading in BOT projects. *Procedia-Soc. Behav. Sci.* **2013**, *104*, doi:10.1016/j.sbspro.2013.11.191.
25. Vaiana, R.; Capiluppi, G.F.; Gallelli, V.; Iuele, T.; Minani, V. Pavement surface performances evolution: An experimental application. *Procedia-Soc. Behav. Sci.* **2012**, *53*, 1149–1160, doi:10.1016/j.sbspro.2012.09.964.

26. Do, M.-T.; Tang, Z.; Kane, M.; de Larrard, F. Pavement polishing—Development of a dedicated laboratory test and its correlation with road results. *Wear* **2007**, *263*, 36–42, doi:10.1016/j.wear.2006.12.086.
27. Do, M.-T.; Tang, Z.; Kane, M.; de Larrard, F. Evolution of road-surface skid-resistance and texture due to polishing. *Wear* **2009**, *5–6*, 574–577, doi:10.1016/j.wear.2008.04.060.
28. Pranjić, I.; Deluka-Tibljaš, A.; Cuculić, M.; Šurdonja, S. Influence of pavement surface macrotexture on pavement skid resistance. *Transp. Res. Procedia* **2020**, *45*, 747–754, doi:10.1016/j.trpro.2020.02.102.
29. Wang, H.; Flintsch, G.W. Investigation of Short- and Long-Term Variations of Pavement Surface Characteristics at the Virginia Smart Road. In Proceedings of the Transportation Research Board 86th Annual Meeting Transportation Research Board, Washington, DC, USA, 21–25 January 2007. Available online: https://trid.trb.org/view/802383 (accessed on 28 May 2021).
30. Road-Conditions-Technote.pdf. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/836188/road-conditions-technote.pdf (accessed on 28 May 2021).
31. Highways England-Network Management Map, January 2020. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/550315/s160308_Network_Manangement_Map.pdf (accessed on 17 June 2021)
32. Zhang, D.; Zou, Q.; Lin, H.; Xu, X.; He, L.; Gui, R.; Li, Q. Automatic pavement defect detection using 3D laser profiling technology. *Autom. Constr.* **2018**, *96*, 350–365, doi:10.1016/j.autcon.2018.09.019.
33. UK Government, Manual of Contract Documents for Highway Works, Volume 1 Specification for HighwayWorks . Available online: https://www.standardsforhighways.co.uk/ha/standards/mchw/vol1/pdfs/2989369%20MCHW%20Vol%201%20Series%20900_web.pdf (accessed on 28 May 2021).
34. Viner, H.; Abbott, P.; Dunford, A.; Dhillon, N.; Parsley, L.; Read, C. Surface texture measurement on local roads. *Publ. Proj. Rep.* **2006**, *PPR148*. Available online: https://trid.trb.org/view/795321 (accessed on 28 May 2021).
35. Gubbins, D. *Time series Analysis and Inverse Theory for Geophysicists*; Cambridge University Press: Cambridge, UK, 2004.
36. MATLAB-MathWorks version 2018a 9.4.0.813654. Available online: https://uk.mathworks.com/products/matlab.html (accessed on 28 May 2021).
37. Highways England-WebTRIS-Map View. Available online: https://webtris.highwaysengland.co.uk/ (accessed on 28 May 2021).
38. Met Office. MIDAS Open: UK Hourly Weather Observation Data, v201901. Centre for Environmental Data Analysis (CEDA), 2019, doi:10.5285/C58C1AF69B9745FDA4CDF487A9547185. Available online: https://catalogue.ceda.ac.uk/uuid/916ac4bbc46f7685ae9a5e10451bae7c (accessed on 17 June 2021).
39. Simpson, I.R.; Jones, P.D. Updated precipitation series for the UK derived from met office gridded data. *Int. J. Climatol.* **2012**, *32*, 2271–2282, doi:10.1002/joc.3397.
40. Weather and Climate Change. Met Office. Available online: https://www.metoffice.gov.uk/ (accessed on 28 May 2021).
41. Kane, M.; Zhao, D.; De-Larrard, F.; Do, M.-T. Laboratory evaluation of aggregate polishing as a function of load and velocity. Application to the prediction of damages on skid resistance of road surfaces due to trucks and passenger cars. *Road Mater. Pavement Des.* **2012**, *13*, 312–326, doi:10.1080/14680629.2011.649424.
42. Car and Truck Tire Wear Particles in Complex Environmental Samples-A Quantitative Comparison with "Traditional" Microplastic Polymer Mass Loads-Abstract-Europe PMC. Available online: https://europepmc.org/article/med/33940753 (accessed on 28 May 2021).
43. Kodippily, S.; Henning, T.F.P.; Ingham, J.M. Detecting Flushing of Thin-Sprayed Seal Pavements Using Pavement Management Data. *J. Transp. Eng.* **2012**, *138*, 665–673, doi:10.1061/(ASCE)TE.1943-5436.0000354.
44. Eberhardsteiner, L.; Füssl, J.; Hofko, B.; Handle, F.; Hospodka, M.; Blab, R.; Grothe, H. Towards a microstructural model of bitumen ageing behaviour. *Int. J. Pavement Eng.* **2015**, *16*, 939–949, doi:10.1080/10298436.2014.993192.