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Influence of Climate and Traffic on the HMA Rut-depth for India

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Abstract

Rutting is one of the major distresses observed in bituminous pavements. In the majority of the design approaches including the Indian Road Congress (IRC) guidelines for the design of bituminous pavements, the rut depth is predicted by limiting the vertical compressive strain at the top of the subgrade. Here, due consideration is not given to the rutting in individual layers of pavement. There are more than 20 variables that influence rutting in the pavement with the degree of influence of the variables differing for each layer. The analysis performed in this study is limited to the rutting observed in bituminous layers (HMA rutting) and the factors influencing it. There are a number of factors that influence the HMA rutting, and among them, traffic and climatic characteristics play a critical role. In this study, traffic data was collected for 12 National Highways across India, and appropriate weather stations were identified. Detailed weather data was collected for all these locations on an hourly basis. Using this information, simulations were carried out in AASHTOWare to generate the rut depth data. For the HMA rutting, it was seen that the pavement temperature distribution played a critical role compared to the maximum pavement temperatures. The degree of influence of Average Annual Daily Truck Traffic (AADTT) on the HMA rutting was however found to strongly depend on the pavement temperature.

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Keywords: Rutting; AASHTOWare; AADTT; AAPT

1. Introduction

India has the second largest road network in the world. The National Highways have a length of 96,260 km, which comprises 1.7% of the total road length and these highways carry more than 40% of the total traffic (NHAI, 2016a). As part of the National Highway Development Project (NHDP), 46,902 km are under construction, and most of the highways are bituminous pavements (NHAI, 2016b). In such bituminous pavements, rutting is one of the commonly observed distresses, considering the extreme temperatures and traffic conditions prevailing in India.

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The bituminous pavements in India are designed as per the guidelines suggested by the Indian Roads Congress (IRC:37, 2012). This design approach considers only vertical compressive strain at the top of the subgrade for predicting the total rut depth as shown in Equation 1.

$$\varepsilon_p = aN^b, \quad (1)$$

where ε_p is the plastic strain, N is the number of standard axle load repetitions, and a and b are constants.

In this model, traffic is considered in terms of the number of repetitions of the standard axle load and the climate is considered in terms of the Annual Average Pavement Temperature (AAPT). These are the only two parameters that are explicitly considered in such design approaches. The total rutting observed in the pavement is however the cumulative effect of the rutting seen in all the individual layers. Though the deformation in all the layers of the pavement contributes to total rutting, the bituminous layer rutting (also known as HMA rutting) has a significant contribution to the total rutting (FWA et al., 2004). Hence, the rutting in bituminous layers should be given due consideration in the design of bituminous pavements. Most of the design strategies across the world except few (for instance the M-E PDG framework adopted in the USA), do not consider the rutting in individual layers. The studies conducted by Kim et al., (2005) showed that there are around 23 variables that influence rutting in bituminous pavements. These parameters can be grouped into traffic, climate, material related parameters, and thickness of different layers. In this study, the focus is on the rutting in bituminous layers and the parameters influencing this rutting, namely traffic and climate.

Among the various factors related to climate, the pavement temperature plays a critical role. Leahy et al. (1989) have shown that among the different parameters considered for the development of the rutting model, the pavement temperature was observed to have a greater impact on the rut depth. India has a widely varying climate with Northern part of India experiencing extreme climatic conditions, while the southern part of India mostly experiences moderate climate throughout the year. For the design of pavements in India, AAPT is currently considered as the representative parameter for the climatic conditions prevailing in any location. India has a wide range of climatic conditions, and it is noteworthy to point out here that one can identify two locations having similar AAPT but diverse climatic characteristics. For instance, Jaipur and Visakhapatnam have an AAPT of 36.2 and 36.7°C respectively while the maximum and minimum air temperatures are 45.8 and 0.7°C for Jaipur and 37.45 and 15.2°C for Visakhapatnam.

The AAPT calculated from Average Annual Air Temperature (AAAT) is not a representative measure of the climatic condition prevailing in a location. M-E PDG suggested using the 7-day average maximum pavement temperature as a representative parameter of climate for specifying the failure criterion for rutting based on the binder tests (Kennedy et al., 1994). In the latter part of this study, it will be shown that one should be considering the entire pavement temperature distribution and not specific temperatures to characterize rutting. The water table depth is another important parameter which is not considered in IRC:37-2012 (2012). One can expect a significant loss in modulus of the granular layers resulting in a weak base if the effect of the water table is not given due consideration.

For traffic, studies conducted by Kim et al., (2005); Blab and Harvey, (2002); Hua and White, (2002); and Hossain et al., (2016) showed that some of the traffic characteristics such as Average Annual Daily Truck Traffic (AADTT), traffic speed, tire pressure, tire type, axle load and configuration and traffic wander influences bituminous layer rutting. Nevertheless, in India, the diverse traffic observed is converted into Equivalent Standard Axle Load (ESAL) repetitions and the number of standard axle load is used for design. The equivalency concept (specification of the Equivalent Axle Load Factor (EALF) parameter) in terms of fourth-power currently used in IRC:37-2012 (2018) was proposed by Deacon (1969). The EALF however is not a constant depending on the axle load alone. EALF was observed to vary depending on the type of pavement, thickness of pavement and the terminal failure conditions (Huang, 2009). The vehicle speed is another important factor as far as rutting in bituminous layers is concerned. Corte et al. (1994) stated that for a 10 km/h increase in vehicle speed from 38 to 48 km/h, 5 to 30% reduction in rut depth was observed depending on the type of pavement. The effect of overloading is also reported in the literature. Elsewhere, it has been shown that heavier trucks with multiple axles caused more rutting compared to single and tandem axles (Hassan K. Salama and Lyles, 2006). About 15 to 25% of the overloaded axles have been observed to cause more than 60% of damage to the pavements (CSIR, 1997). In the same study, it has also been shown that a standard axle of 9 tons carrying twice the axle load has 18.4 times higher damaging effect on the pavement.

It is tedious to consider the influence of all these parameters on the rut depth using the current design strategy adopted for India. A straightforward estimation of the combined influence of variables such as axle load, pavement temperature, axle overloading and traffic speed cannot be made here. Supportive tools such as design software have to be used for this purpose. Different software tools have been developed to implement the design strategies adopted in various countries. Few such software tools available are CIRCLY (2018), MePads (2007) and AASHTOWare (2012) based on the design strategies adopted in Australia, South Africa, and the USA. Compared to the other two software tools, AASHTOWare is a comprehensive pavement design software which has detailed consideration related to traffic, climate and material properties. Considering its versatility, in this study, AASHTOWare is used to analyze the influence of different variables on rut depth observed for highways in India.

AASHTOWare was developed based on the ME-PDG framework (M-EPDG, 2004). There are at least five distresses that have detailed consideration in AASHTOWare, namely, total rutting, bituminous layer rutting, top-down cracking, bottom-up fatigue cracking and thermal cracking. The rutting model used in AASHTOWare is as shown below.

$$\Delta = \varepsilon_p\, h = \beta_{1r}\, k_z\, \varepsilon_r\, 10^{k1r}\, n^{k2r\,\beta 2r}\, T^{k3r\,\beta 3r}, \tag{2}$$

where Δ is the deformation in the HMA layer, ε_p is the plastic strain in the HMA layer, h is the thickness of the HMA layer; ε_r is the resilient strain in HMA layer, n is the number of standard axle load repetitions, T is the mix or pavement temperature, k_z is the depth confinement factor, k_{1r}, k_{2r}, k_{3r} are the global field calibration parameters and β_{1r}, β_{2r}, β_{3r} are the local or mixture field calibration parameters.

For traffic, AASHTOWare requires the total axle load spectrum, axle load distribution and monthly variation in traffic as input parameters for the traffic data. Incremental damage approach is used, and the rutting is calculated separately for a given vehicle type, axle type in that vehicle class and the specific axle load group. The actual axle in any load group is placed on the pavement, and the stresses and strains are evaluated. The issues related to the calculation of equivalency factors are addressed in AASHTOWare. For each such calculation, the climatic condition prevailing in that period is provided appropriately. The climate data includes air temperature, rainfall, humidity, wind speed, sunshine and water table depth for every hour collected for two consecutive years. Based on this information, the variation in the subgrade modulus and the resilient modulus of the granular layers due to the variation in water table depth is calculated periodically. Also, the dynamic modulus of the bituminous layer is calculated considering the variation in pavement temperature spatially and with time. Since bituminous mixture exhibits a viscoelastic response, the variation in material properties due to variation in speed is also considered accordingly.

The rutting model present in AASHTOWare is provided with local and global calibration factors to take into account the variability in the material and the laboratory to field variations. The variation in predicted distress from the field to the laboratory is accounted by local calibration factors and the variability in material property tested across different laboratories is taken into consideration by global calibration factors. The default calibration constants of the distress models used in AASHTOWare were calibrated exclusively for the USA conditions. The use of default calibration factors has been observed to over-estimate the rut depth in the pavements (Banerjee et al., 2009; Jannat et al., 2016). The global calibration constants can be calculated from repeated creep and recovery experiments performed in the laboratory. For estimation of local calibration constants, field data related to rutting is necessary. In this study, only the global calibration constants were calculated for India.

To summarize, the main focus of this study is to highlight the influence of traffic and climatic factors on the HMA rut depth for Indian Highways. For this purpose, the traffic and axle load data for 12 National Highways along with the respective climate data in the suitable formats were input in AASHTOWare. Simulations were carried out using the global calibration factors calculated (for the rutting model) for India (Bhanoj, 2016). A detailed analysis of the simulation results for all these highways was carried out to ascertain out the influence of traffic (AADTT and overloading of axles) and climatic factors (pavement temperatures) on HMA rutting.

2. Data collection

2.1. Preliminary data collection

2.1.1. Traffic data

Table 1 shows the traffic data (expressed in terms of AADTT), and the axle load data for 12 National Highways collected from V. R. Techniche, 2015. For NH-5 alone, this data was collected at two different locations. Hence, to differentiate them, the first location will be represented as NH-5(A) and the second location will be represented as NH-5(B). Table 1 also shows the Equivalent Standard Axle Load (ESAL) values calculated using AADTT and Vehicle Damage Factor (VDF), based on the procedure specified in IRC:37-2012 (2012). The design period for calculation of the ESAL values is considered as ten years for all the highways except for NH-5(A) and NH-58. For NH-5(A) and NH-58, the ESAL values for the design life of 10 years exceed the maximum limit of 150 Million Standard Axles (MSA) specified in IRC:37-2012 (2012) and hence the design period is reduced to 7 and 5 years respectively. From Table 1, one can find that the AADTT value has a wide variation ranging from 743 to 8541 trucks/day and thereby the ESAL values also range from 9 MSA to 138 MSA.

The overloading analysis of the axle load data (Table 2) revealed that more than 50% of the tandem and tridem axles are overloaded when compared to the legal axle load specified in IRC:3-1983 (2009). To quantify the extent of overloading, a parameter known as, Average Overloading Ratio (AOLR) as suggested by Wen et al. (2005) is calculated. In the current study, AOLR is calculated as the average of the overloading ratio for axles carrying a load heavier than the legal axle load for each of the axle type. Here, the overloading ratio is calculated as the ratio of actual axle load to the legal axle load specified in IRC:3-1983 (2009). Table 2 also shows the AOLR values calculated for the single-axle with single-wheel (SS), single-axle with dual-wheel (SD), tandem and tridem axles. One should notice that the AOLR value (Table 2) for tandem axles of NH-58 and tridem axles of NH-5(A) are greater than 2. This implies that, on an average, these axles carry more than twice the legal axle load. For the sake of simplicity, ΣAOLR shown in Table 2 will henceforth be referred to as simply "AOLR."

Table 1.Traffic details of National Highways

Highway	From-To (Length in km)	Data collection location	AADTT (Trucks/Day)	ESAL (MSA)
NH-2	New Delhi-Kolkata (1465)	Anantram toll plaza	1969	15
NH-3	Agra-Mumbai (1190)	Jajau toll plaza	1969	17
NH-5(A)	Jharpokharia-Chennai (1533)	Kallaparu toll plaza	8541	138
NH-5(B)	Jharpokharia-Chennai (1533)	Nallur toll plaza	6193	46
NH-13	Solapur-Mangaluru (691)	318 km in the Hospet to Chitradurga stretch	6975	64
NH-15	Samakhiali-Pathankot (1526)	Southbound direction at 133rd km	2615	44
NH-58	New Delhi-Mana Pass (538)	Shivaya toll plaza	6639	128
NH-65	Ambala-Pali (881)	Kaithal	1693	23
NH-69	Nagpur-Obedullaganj (350)	Obedullaganj	3826	35
NH-79	Ajmer-Indore (500)	189th km in the South bound direction	6230	48
NH-113	Nimbahere-Dahod(240)	Neemuch	743	9
NH-207	Hosur-Dobbaspet (155)	126thkm from Dobbaspet	1766	15

Table 2. Percentage of overloaded axles and AOLR for each axle type

Axle type	NH-2	NH-3	NH-5(A)	NH-5(B)	NH-13	NH-15	NH-58	NH-65	NH-69	NH-79	NH-113	NH-207
					Percentage of overloaded axles							
SS	28	42	49	21	49	39	42	24	36	54	26	24
SD	27	39	49	26	23	22	25	16	58	47	30	35
Tandem	81	77	80	42	95	80	84	81	89	93	58	66
Tridem	80	56	80	56	100	58	100	64	-	76	50	56
					AOLR							
SS	1.10	1.09	1.38	1.20	1.16	1.15	1.37	1.13	1.09	1.06	1.07	1.18
SD	1.20	1.17	1.47	1.37	1.19	1.33	1.39	1.19	1.19	1.10	1.17	1.25
Tandem	1.20	1.21	1.49	1.29	1.20	1.66	2.04	1.32	1.20	1.17	1.29	1.27
Tridem	1.32	1.21	2.08	1.42	1.36	1.53	1.50	1.61	1.09	1.19	1.32	1.16
ΣAOLR	4.82	4.68	6.42	5.28	4.91	5.67	6.30	5.25	4.57	4.52	4.85	4.86

2.1.2. Climate data

Depending on the geographical proximity of the data collection location of the highways (Table 1) considered in this study, each highway was mapped with a weather station as shown in Table 3. For each weather station, the corresponding daily maximum air temperature (AT_{max}), daily minimum air temperature (AT_{min}), daily maximum pavement temperature (PT_{max}), daily minimum pavement temperature (PT_{min}), Average Annual Pavement Temperature (AAPT) and the water table depth are given in Table 3. The daily maximum and minimum air temperatures were collected from the database available with Indian Meteorological Department, Pune (IMD Pune, 2011). The water table depth was obtained from the report published by the Central Ground Water Board (2011). The daily maximum and minimum pavement temperatures were calculated using the model provided by Nivitha and Krishnan (2014).

From Table 3, one can see the wide variation in the climatic characteristics of different regions. The maximum air temperature (AT_{max}) ranges from 35.0 to 45.9ºC, and the AT_{min} ranges from 0.0 to 18.1ºC. Similarly, the PT_{max} ranges from 46.3ºC to 62.4ºC, and the PT_{min} ranges from 2.8 to 24.3ºC. If one compares locations having identical maximum air temperature, say, for instance, Amritsar (AT_{max} of 45.9ºC) and Chennai (AT_{max} of 45.0ºC), the minimum air temperatures differ considerably with Amritsar having an AT_{min} of 0ºC and Chennai having an AT_{min} of 17.6ºC. The water table depth of different regions also varies from a maximum of 50 m to a minimum of 2.1 m.

Table 3. Details of weather station mapped for each highway

Highways	Weather station	AT_{max} (ºC)	AT_{min} (ºC)	PT_{max} (ºC)	PT_{min} (ºC)	AAPT	Water Table (m)
NH-15, NH-65	Amritsar	45.9	0.0	62.4	2.8	37.3	3
NH-207	Bengaluru	36.8	10.0	48.6	13.7	32.9	5.0
NH-69, NH-113	Bhopal	42.5	2.6	57.2	5.2	35.3	5.5
NH-5(B)	Chennai	45.0	17.6	59.3	23.7	40.3	4.3
NH-3, NH-79	Jaipur	45.8	0.7	61.9	3.2	36.2	50.0
NH-58	Lucknow	43.2	6.2	58.5	10.3	35.8	10.0
NH-13	Mangaluru	35.0	18.1	46.3	24.3	36.3	2.1

NH-2	New Delhi	44.3	1.5	60.1	4.4	35.4	9.7
NH-5(A)	Visakhapatnam	37.4	15.2	49.9	21.0	36.7	5.0

2.1.3. Cross-sections

Appropriate cross-sections for each highway were chosen based on the design procedure specified in IRC:37-2012 (2012). ESAL values provided in Table 1 and AAPT values provided in Table 3 were considered for determining these cross-sections. The design thickness for each highway is given in Figure 1. These cross-sections will be used in AASHTOWare for carrying out the simulations.

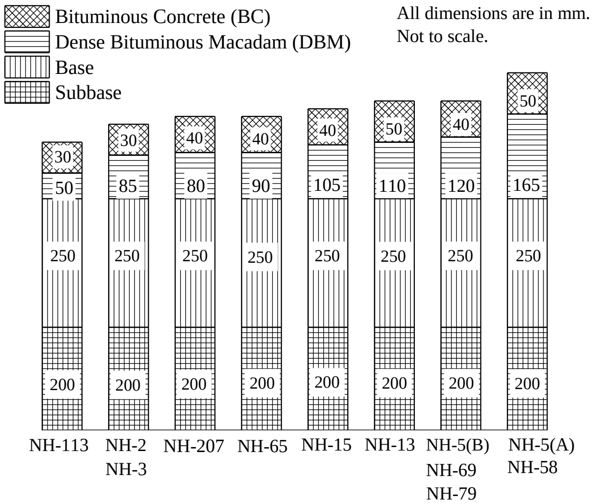

Figure 1. Choice of the cross-section from IRC:37-2012 (2012)

2.2. Data collection for AASHTOWare simulation

2.2.1. Traffic input

The traffic input for AASHTOWare demands four main parameters; they include the volume of truck traffic, vehicle speed, axle load distribution and other parameters related to axle and wheel configurations. The vehicle classification used in AASHTOWare is in accordance with the Federal Highway Agency (FHWA) vehicle classification (FHWA, 2001). However, there are some vehicle configurations in India (IRC:3-1983, 2009) which do not have an equivalent axle configuration as per FHWA (2001). In such cases, the closest axle load configuration from FHWA was chosen and modified to the existing IRC axle configuration by adjusting the axles per truck. For each of the vehicle class, the volume of truck traffic and the axle load distribution are required to be specified separately. The AADTT value was assumed to have a linear growth rate of 5%. The monthly adjustment factor was taken as one with an assumption that traffic is distributed equally for all the months. A tire pressure of 560 kPa was used as specified in IRC:37-2012 (2012). The axle load distribution was calculated separately for each vehicle class and different axle types in each class. All the other default values provided in AASHTOWare were used for the parameters related to wheel and axle configurations.

2.2.2. Climate database

AASHTOWare requires detailed information regarding air temperature, humidity, wind speed, sunshine, and rainfall on an hourly basis for two years to perform simulations. All such information were collected from Indian Meteorological Department, Pune (IMD Pune, 2011) for the nine weather stations (Table 3). Moreover, the data of maximum global radiation, sunrise and sunset time were required on a daily basis. From sunshine data, the global radiation was calculated using Angstrom-Prescott model with the constants recalculated for India (Srivatsava and Pandey, 2013). The water table depth for a minimum of four seasons is also required to be input in the AASHTOWare software. Finally, the climatic database relevant to India was created by sorting and arranging all the information mentioned above in a specified .xml format.

2.2.3. Material properties

In AASHTOWare, the dynamic modulus is specified for the bituminous layers (Bituminous Concrete (BC) and Dense Bituminous Macadam (DBM)), and the resilient modulus is specified for granular layers. The dynamic modulus of bituminous mixtures was measured using an Asphalt Mixture Performance Tester (AMPT). For this test, the samples were prepared using the mid-gradation of BC-Grade II and DBM- Grade II (MORTH, 2013) with the nominal maximum aggregate sizes of 13 mm and 26.5 mm respectively. An unmodified binder of VG30 grade (IS:73, 2013) was used for the bituminous layers. This binder has properties identical to that of AC-30 as per ASTM D3381 (2013). Bituminous mixture samples were fabricated with 5% binder content for BC-Grade II and 4.5% binder content for DBM-Grade II and the samples were compacted to a target air voids of 4±0.5% air voids content using a shear box compactor (ASTM D7981, 2015). The compacted prismatic specimen has a dimension of 450 mm length, 150 mm width and 145-185 mm height. Three cylindrical samples with a dimension of 150 mm height and 100 mm diameter were cored and sliced from one shear box compacted prismatic specimen. The dynamic modulus test was performed for these samples as per AASHTO T 378 (2017). The dynamic modulus for BC and DBM mixes was measured separately for frequencies ranging from 0.01 to 25 Hz and temperatures ranging from 5 to 55°C in increments of 10°C. Table 4 shows the dynamic modulus values for BC and DBM mixes at different frequencies and temperatures.

The resilient modulus (M_R) was calculated for the granular layers (base, subbase, and subgrade) from IRC:37-2012 (2012) for an assumed California Bearing Ratio (CBR) of 10% for the subgrade. The resilient modulus calculated for the base and subbase is 234 MPa while that for the subgrade is 75 MPa.

Table 4. Dynamic modulus for bituminous mixtures (in MPa)

	Frequency (Hz)					
Temperature (°C)	0.01	0.2	2	5	20	25
VG30 (BC)						
5	8985	16526	22365	24516	27522	28003
15	2577	7266	12244	14438	17906	18462
25	531	2462	6149	8041	11230	11735
35	172	659	2115	3189	5361	5684
45	124	262	780	1277	2552	2756
55	76	111	236	360	757	906
VG30 (DBM)						
5	9190	16087	21483	23545	26301	26696
15	2309	7136	12472	14835	18559	19175
25	446	1922	5267	7165	10415	10946
35	127	506	1809	2855	5036	5323
45	80	190	631	1077	2299	2547
55	65	90	206	346	775	960

2.2.4. Global Calibration Constants

In this paper, the global calibration constants developed for Indian conditions were used instead of the default values provided in AASHTOWare. These India specific calibration constants were calculated by Bhanoj (2016) for “confined” and “unconfined” conditions. More details related to confinement conditions and the method of calculation of calibration factors can be obtained from Bhanoj (2016). In this study, the global calibration constants developed for “unconfined” condition is used. The material specific global calibration constants, k_{r1}, $k_{r2,}$ and k_{r3}, for the unconfined condition are -2.205, 0.818 and 0.468 respectively.

2.3. Simulations using AASHTOWare

In this study, simulations were carried out in AASHTOWare for the data corresponding to each of the National Highways. The cross-sections shown in Figure 1 are analyzed in AASHTOWare for the respective traffic (Table 1), weather conditions (Table 3) and the material properties (Section 2.2.3 and Table 4). The speed of the vehicle was specified as 40 km/h for all the simulations. All the highways were assumed to have a total of four lanes with two lanes in each direction. The percentage of trucks in the design direction was assumed to be 50%, and it was assumed that out of this 50% of trucks, 75% uses the design lane. A total of 12 simulations were performed in AASHTOWare to estimate the influence of climate and traffic parameters on HMA rutting.

3. Analysis and Discussion

The influence of climate and traffic characteristics on the HMA rut depth is discussed in this section. In such comparisons, one parameter is varied at a time. Cross-sections with different thicknesses can be compared here, as the criterion for the design of each cross-section remains the same; i.e., each cross-section is designed to carry the stipulated traffic in the specified design period with the rutting in each of them limited to 20 mm.

3.1. Influence of climate

3.1.1. Water table depth

To discuss the influence of water table depth, two highways, NH-15 and NH-79 are considered as shown in Figure 2. The water table depth is 50 m for NH-79 while it is 3 m for NH-15. These two highways exhibit identical pavement temperature ranges as seen from the Figure 2. The AADTT is higher for NH-79, and hence intuitively, one can expect NH-79 to exhibit higher rutting compared to NH-15. However, Figure 2 shows that the total rutting is higher for NH-15 by 4.78 mm. This can be attributed to the influence of water table depth. The lower water table depth for NH-15 results in increased rutting in granular layers and hence a higher total rutting for NH-15. However, if one compares the HMA rutting as shown in Figure 2, it can be seen that the HMA rutting is higher in NH-79 compared to NH-15. Since the focus of this investigation is on HMA rutting, discussions will be limited henceforth only to HMA rutting.

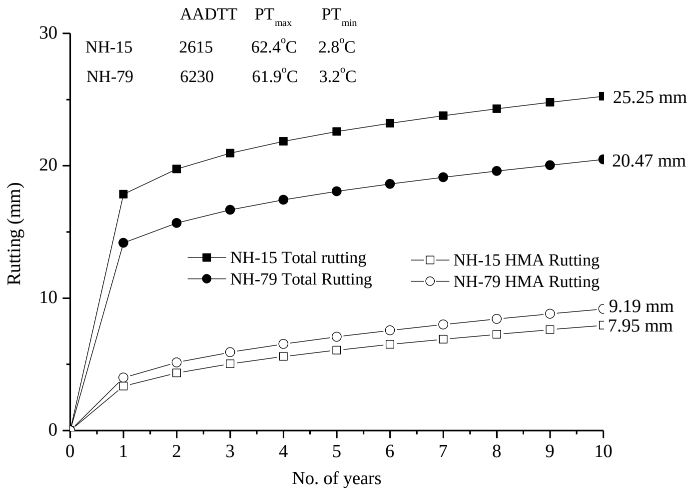

Figure 2. Influence of water table depth on the rut depth

3.1.2. AAPT and Pavement temperature distribution

The guidelines for flexible pavement design in India, IRC:37-2012 (2012) uses the AAPT vales for the design of flexible pavements. The HMA rut depth for two highways, NH-13 and NH-79 with identical AAPT and AADTT values are compared as shown in Figure 3. It can be seen that the HMA rut depth is higher for NH-79 by 4.71 mm compared to NH-13. Though both Jaipur (NH-79) and Mangaluru (NH-13) exhibit identical AAPT values, the temperature ranges are different for both locations. For Jaipur, the pavement temperature ranges from 61.9 to 3.2ºC while that for Mangaluru ranges from 46.3 to 24.3ºC. The higher frequency of pavement temperatures for Jaipur in the temperature range between 46 to 62ºC results in higher rutting for NH-79. To show the influence of the maximum pavement temperatures, two locations with identical PT_{max} are compared as shown in Figure 4.

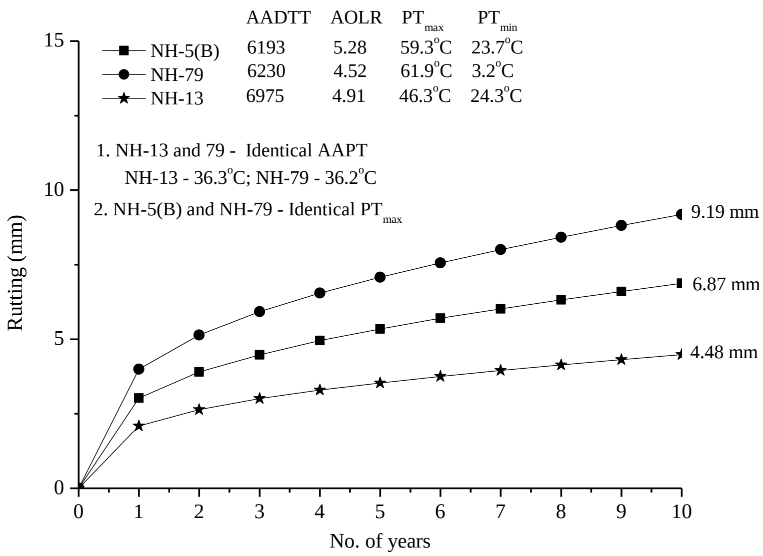

Figure 3. HMA rut depth for NH-5(B), NH-79 and NH-13

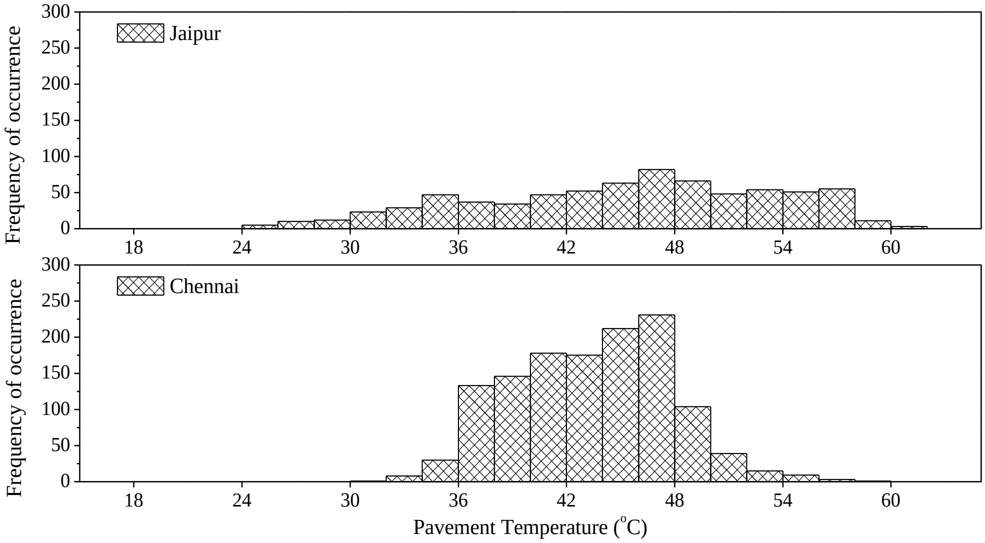

Figure 4. Pavement temperature distribution for Jaipur and Chennai (for two years)

NH-5(B) and NH-79 pass through locations exhibiting identical PT_{max} (59.3 and 61.9°C respectively) and different PT_{min} (23.7 and 3.2°C respectively) as shown in Figure 3. The AADTT and AOLR are similar for the two highways. It can be seen from this figure that, the HMA rutting is higher for NH-79 by 2.32 mm compared to NH-5(B). The daily maximum pavement temperature distribution for these two locations is shown in Figure 3 for two years. It is seen that the daily maximum pavement temperatures are concentrated in the temperature range between 36 to 50°C for Chennai while the same for Jaipur ranges between 34 to 58°C. The temperatures above 54°C occur for 60 days in a year for Jaipur while the same occurs for about five days in a year for Chennai.

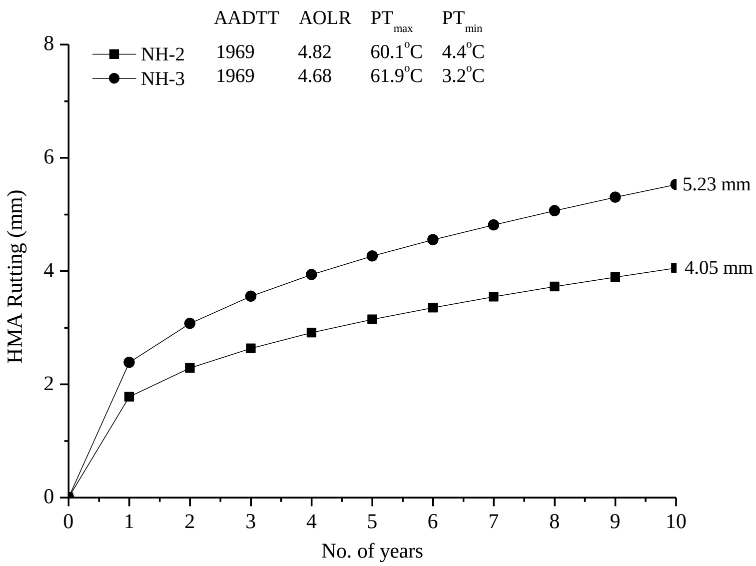

Figure 5. Influence of high air temperatures on the HMA rut depth

Similarly, the pavement temperature distribution also plays a critical role. To highlight the influence of pavement temperature distribution, two highways, NH-2 and NH-3, passing through New Delhi and Jaipur respectively are considered. Figure 5 shows the HMA rut depth values for NH-2 and NH-3. One can see that the HMA rutting is found to be higher for NH-3 by 1.48 mm compared to NH-2. The pavement temperature distribution for the two locations, Jaipur and New Delhi, is shown in Figure 6. It is seen that though both locations have identical PT_{max} and PT_{min}, the temperature distribution is not the same. For instance, the number of days the pavement temperature is greater than 55ºC is 60 days/year for Jaipur while the same is 31 days/year for New Delhi. The design criteria for rutting are generally specified with the focus only on the maximum pavement temperatures. For instance, the performance grade specification for the binders adopted in the USA (Kennedy et al., 1994) specify the failure criteria for rutting, $G^*/\sin\delta$ at the 7-day average maximum pavement temperature as discussed in the introduction. It is seen here that the rutting behavior is not similar for locations with identical PT_{max} (see Figures 3 and 5). Ideally one should consider the entire temperature range rather than the extreme temperature values for design. The number of days for which such extreme temperatures are observed also should be taken into account for a precise estimation of the rutting.

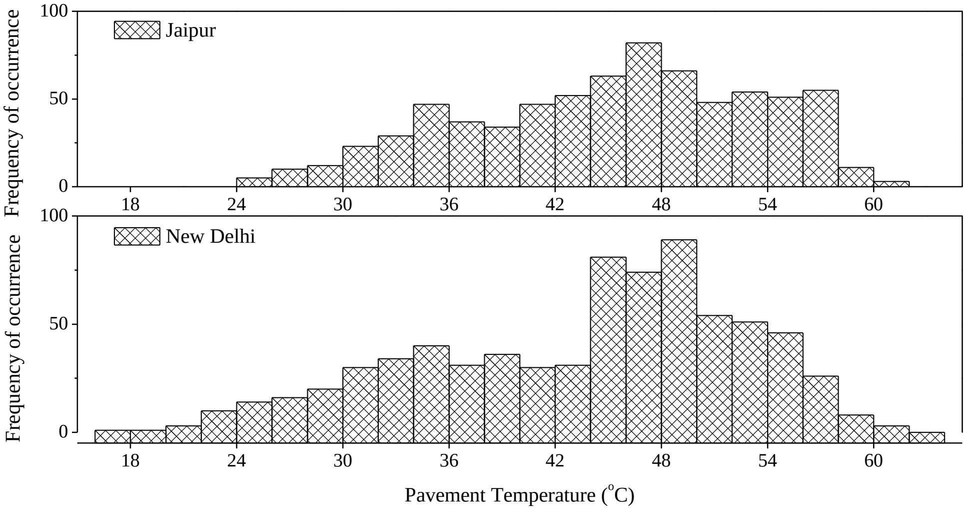

Figure 6. Pavement temperature distribution for Jaipur and New Delhi (for two years)

3.2. Influence of traffic

3.2.1. ESAL

The ESAL is a commonly used representation of the traffic characteristics of a highway for the design of the flexible pavements. IRC:37-2012 (2012) also specifies identical cross-sections for highways with identical ESAL values. To illustrate the influence of ESAL on the HMA rut depth, two highways, NH-3 and NH-207 are considered as shown in Figure 7. It can be seen that there is a difference in a rut depth of about 1.85 mm between the two highways. From Figure 7 it is seen that; the pavement temperatures, PT_{max} and PT_{min} are different for these two locations. To remove the influence of pavement temperature, NH-79 and NH-15 exhibiting identical ESAL values and pavement temperatures (PT_{max} and PT_{min}) are compared as shown in Figure 8. However, the rut depth for NH-79 is higher by 1.24 mm compared to NH-15. It was seen that though the ESAL values are identical, the AADTT and AOLR for these highways are different. For instance, the AADTT and AOLR for NH 79 is 6230 trucks/day and 4.52 respectively while the same for NH-15 is 2615 trucks/day and 5.67 respectively.

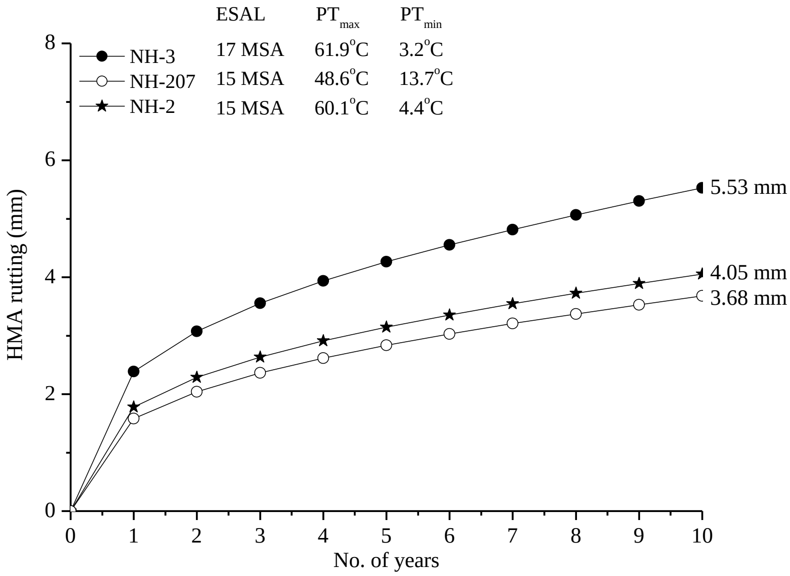

Figure 7. Comparison of HMA rut depth for highways NH-3, NH-207, and NH-2 with identical ESAL

From this figure, it can be seen that these two highways exhibit identical ESAL values and pavement temperatures. However, the rut depth for NH-79 is higher by 1.26 mm compared to NH-15. The AADTT, overloading characteristics and the pavement temperature distribution of these two highways are completely different despite them exhibiting identical ESAL values.

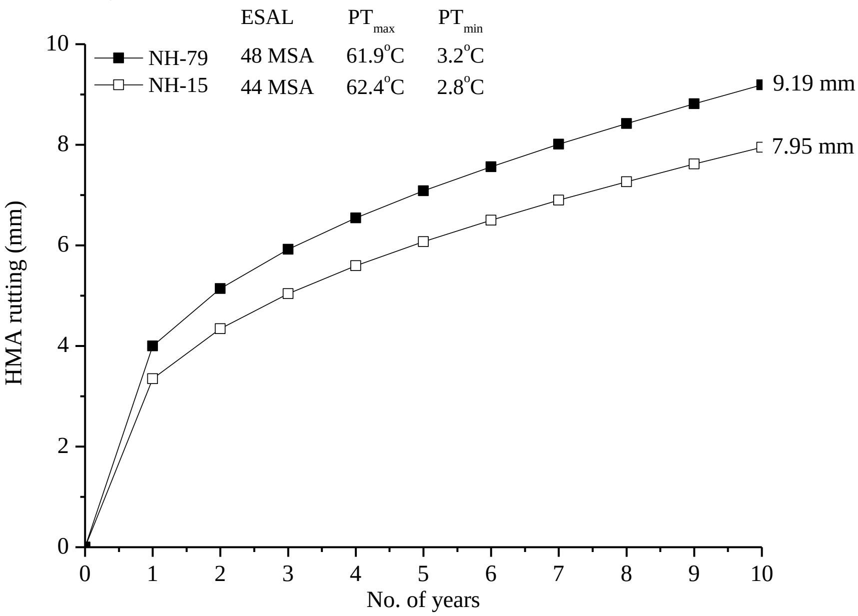

Figure 8. Comparison of HMA rut depth for highways NH-79 and NH-15 with identical ESAL

To further clarify in this regard, NH-3 exhibiting identical PT_{max}, PT_{min}, AADTT and AOLR is now compared with NH-2 as shown Figure 7. The AADTT and AOLR for NH-2 is 1969 trucks/day and 4.82 respectively and that for NH-3 is 1969 trucks/day and 4.69 respectively. For these two highways, it is seen that the difference in rut depth is 1.48 mm. From this analysis, one can see that the HMA rut depth is not identical for locations with identical pavement temperature ranges, AADTT and AOLR values. The variation in the pavement temperature distribution as discussed earlier should be considered here. For the moment, the detailed discussion related to climate can be neglected, and the climatic characteristics of the locations are compared in terms of the maximum and minimum pavement temperatures. The influence of AADTT and overloading on the HMA rut depth is discussed in the subsequent section.

3.2.2. AADTT

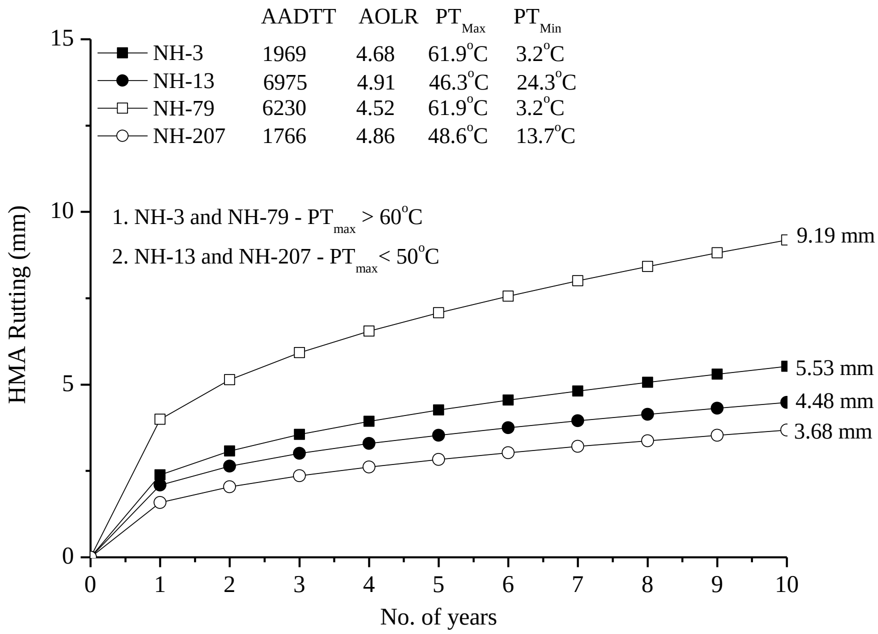

Figure 9. Influence of AADTT on the HMA rut depth

To highlight the influence of AADTT on the total rut depth, four highways are considered as shown in Figure 9. The four highways can be grouped into two sets as illustrated in the same figure. The first set is NH-3 and NH-79, both passing through Jaipur. The second set is NH-13 and NH-207, passing through Mangaluru and Bengaluru with identical climatic characteristics. It is also seen that both sets of locations have identical AADTT ranges (1969 and 6230 trucks/day for the first set and 1766 and 6975 trucks/day for the second set). From Figure 9 it is seen that the difference in rut depth between the two highways in the first set is 3.66 mm while that between the second set is 0.8 mm. This shows that for identical variations in AADTT, the influence of rut depth is higher for pavements with higher pavement temperatures (PT_{max} >60ºC) compared to those with lower pavement temperatures (PT_{max} <50ºC).

3.2.3. Overloading

The effect of overloading is illustrated by comparing two different highways, NH-5(A) and NH-13 as shown in Figure 10. NH-5(A) exhibits higher overloading for all the four axles compared to NH-13 as seen from Table 2. It is seen that the rut depth is higher for NH-5(A) by 1.68 mm compared to NH-13. However, for the same highways, NH-5(A) and NH-13 it is seen that the percentage of overloaded axles are higher for NH-13 while the average overloading ratio for all the axles is higher for NH-5(A) (Table 2). It is difficult to represent the overloading characteristics of highways by a unique parameter as both the percentage of overloaded axles and the magnitude of overloading have serious consequences on the HMA rutting. Hence additional parameters which take into effect the combined variation in the percentage of overloaded axles and the overloading ratio have to be specified.

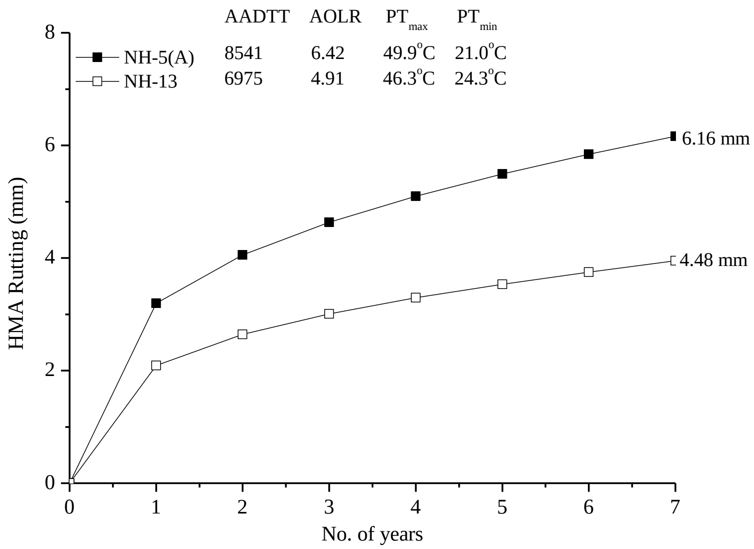

Figure 10. Effect of overloading on HMA rut depth

4. Summary and conclusions

In this study, the influence of traffic and climatic characteristics on the HMA rut depth was analyzed for 12 National Highways in India. The traffic data in terms of the AADTT and the overloading characteristics were collected for the 12 National Highways, and appropriate weather stations were identified for each highway. Simulations were carried out using AASHTOWare, and the rut depth data pertaining to these highways were generated. Different cases were identified and discussed to highlight the influence of traffic and climatic characteristics on the rut depth. The salient observations based on the analysis performed in this study are summarized below:

- The rutting in granular layers was observed to be significantly influenced by the water table depth. This masked the influence of climate and traffic on the total rut depth for certain highways.
- Highways with identical AAPT values (Jaipur and Mangaluru with AAPT of 36.2 and 36.3°C respectively) did not exhibit identical rut depth. The difference in rut depth of 4.71 mm was attributed to the difference in temperature ranges ranging from 61.9 to 3.2°C for Jaipur and 46.3 to 24.3°C for Mangaluru.
- Locations with identical maximum pavement temperatures (Jaipur and Chennai) did not exhibit identical rut depth. The pavement temperature distribution for these two locations played a critical role here. The pavement temperatures in Jaipur were greater than 54°C for 60 days/year while the same for Chennai was five days/year.
- The HMA rut depth was observed to be different for highways with identical ESAL values and pavement temperature ranges. The AADTT ranges, overloading characteristics and the pavement temperature distribution are different for such highways.
- The influence of AADTT on the HMA rut depth was observed to be higher for locations with higher pavement temperatures (PT_{max} >60°C) compared to the locations with relatively lower pavement temperatures (PT_{max} <50°C).
- The effect of overloading could not be represented by a single parameter as one has to consider the effect of percentage and the magnitude of overloading. Additional parameters that combine the influence of the percentage of overloading and the overloading ratio have to be specified.

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