

Unsaturated Soil Behavior Under Repeated Traffic Loading in Arid Climates: A Scenario-Based Numerical Study of Road Subgrade Performance Under Assumed Climate-Analogue Suction Pathways

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Abstract

Road subgrade response in arid regions is governed by the unsaturated state of the soil, yet pavement design frameworks represent moisture mainly through empirical, largely equilibrium environmental adjustments rather than through the explicit evolution of matric suction during wetting and drying. Climate influence is represented by a two-suction concept that separates the annual-average drying trend from the critical post-rainfall wetted state. The suction pathways are not derived from Coupled Model Intercomparison Project Phase 6 (CMIP6) output: their end-of-life values (140 and 55 kPa) are prescribed, and they are labelled Shared Socioeconomic Pathway (SSP) SSP2-4.5 and SSP5-8.5 analogues only because their direction and ordering are qualitatively consistent with the projections of the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) for arid regions. They are treated throughout as assumed scenario parameters. All soil, traffic and deformation parameters are representative literature-based values; no measured retention, resilient modulus or rutting data are used, so every result is a conditional model output and not a validated prediction. Under the assumed high-emission analogue the computed year-20 subgrade rut depth is 22.0 mm (parameter-perturbation range 12-31 mm), reaching the 20 mm rut-depth threshold adopted here between years 19 and 20, against 6.5 mm for the constant-climate baseline and 11.1 mm for the moderate analogue. A one-at-a-time sensitivity screening ranks the assumed pathway shift (+15.5 mm) first, followed by design suction (+4.6/-1.8 mm), the initial-strain (ϵ_0) scaling and the exponent β , with traffic growth least influential.

Keywords: unsaturated subgrade, matric suction, resilient modulus, permanent deformation, Tseng-Lytton model.

1. Introduction

In arid and semi-arid regions, the subgrade remains unsaturated for most of its service life, so its stiffness and its resistance to rutting are controlled by matric suction rather than by a single as-constructed moisture state [1], [2]. Pavement design frameworks are not blind to moisture, and it is important to state their treatment of it correctly. The 1993 American Association of State Highway and Transportation Officials (AASHTO) guide handles environmental effects through seasonally adjusted layer coefficients and an empirical

serviceability formulation [3], while the Mechanistic-Empirical Pavement Design Guide (MEPDG) couples the Enhanced Integrated Climatic Model (EICM) to hourly climate data and adjusts the subgrade resilient modulus (M_r) through an environmental factor related to the Thornthwaite Moisture Index (TMI) [4], [5]. The limitation addressed here is therefore narrower and more specific than a claim that these frameworks assume saturated or near-saturated soil mechanics. It is that, in routine application, moisture enters as an empirical and largely equilibrium adjustment: the uptake of water by

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the subgrade and its evolution through successive wetting and drying cycles are not represented explicitly as a suction state, and that state is not propagated into the permanent deformation model that generates the predicted rut depth [5], [6], [7].

The physical reason this matter is well established experimentally. Matric suction contributes to the effective stress and to interparticle capillary bonding, and suction-controlled laboratory testing shows a strong and nonlinear increase of resilient modulus with suction for compacted subgrade soils [1], [2], [8], [9]. The corollary is that an episodic wetting event, which removes suction quickly, reduces stiffness and rutting resistance disproportionately, so a design suction taken from average annual conditions can be non-conservative [10], [11]. Climate change adds a two-sided hydrological problem in arid regions: annual-average soil moisture may fall as evapotranspiration increases, while individual storms may intensify and produce episodic deep wetting of the subgrade [12]–[15]. These two tendencies act on opposite branches of the retention curve, so they cannot be represented by a single moisture trend, and their consequences for a 20-year design life differ in sign.

Three gaps follow from the literature reviewed critically in Section 2. First, subgrade moisture is usually entered as a static design value, or as a bulk seasonal adjustment, rather than as a suction trajectory that evolves over the design life [7], [16]. Second, where climate information has been introduced, it has been used to correct the resilient modulus, but the corrected suction state has not been carried forward into a moisture-scaled permanent deformation model to produce rut depths [1], [7], [16]. Third, the relative contributions of the climate assumption and of the geomechanical model parameters to the predicted rut depth have not been separated, so it is not known whether such projections are governed by the climate input or by calibration uncertainty [17], [18].

This paper addresses those gaps with a transparent and fully traceable simulation framework that couples a Soil-Water Characteristic Curve (SWCC) model, a suction-dependent resilient modulus model and the Tseng-Lytton permanent deformation model, and drives them with a prescribed design-suction pathway and an

Equivalent Single Axle Load (ESAL) traffic growth model over a 20-year design life. The contribution is methodological rather than predictive, and the scope is stated plainly at the outset: no measured soil, traffic or climate data are used, the climate-analogue suction pathways are assumed scenario inputs and not downscaled climate model output, and every reported quantity is a model output conditional on those assumptions. On that basis the paper quantifies the mechanism by which the two-suction concept transfers episodic wetting into rut depth, the resulting year-by-year rut-depth trajectories relative to an adopted 20 mm threshold, and a ranked decomposition of the drivers of the year-20 rut depth. Section 5 states the validation that would be required before the framework is used in design, together with the limitations that follow from the assumptions.

Nomenclature

Abbreviation	Full Form
AADTT	Average Annual Daily Truck Traffic
AADTT ₀	Initial Average Annual Daily Truck Traffic
AASHTO	American Association of State Highway and Transportation Officials
AI	Artificial Intelligence
APT	Accelerated Pavement Testing
AR6	Sixth Assessment Report (IPCC)
CBR	California Bearing Ratio
CMIP6	Coupled Model Intercomparison Project Phase 6
EICM	Enhanced Integrated Climatic Model
ERAPave PP	Elastic Response Analysis of Pavements – Performance Predictions
ESAL	Equivalent Single Axle Load
FE	Finite Element
IPCC	Intergovernmental Panel on Climate Change
MEPDG	Mechanistic-Empirical Pavement Design Guide
NCHRP	National Cooperative Highway Research Program
PSI	Present Serviceability Index
RD	Rut Depth
SSP	Shared Socioeconomic Pathway
SSP2-4.5	Shared Socioeconomic Pathway 2 with 4.5 W/m ² radiative forcing
SSP5-8.5	Shared Socioeconomic Pathway 5 with 8.5 W/m ² radiative forcing
SWCC	Soil-Water Characteristic Curve
TMI	Thornthwaite Moisture Index

Symbol	Definition (unit)
a	Fredlund-Xing fitting parameter related to the air-entry value (kPa)
$C(\psi)$	Fredlund-Xing correction factor (dimensionless)
e	Base of the natural logarithm
g	Annual traffic growth rate (%/yr)
h	Subgrade layer thickness (m)
i	Summation index (design year) in Eq. (12); index of the perturbed input in Eq. (14)
k_1, k_2, k_3, k_4	Regression constants of the resilient modulus model, Eq. (6) (dimensionless)
M_r	Resilient modulus (MPa)
m, n	Curve-shape parameters of the van Genuchten and Fredlund-Xing models (dimensionless)
N	Number of load repetitions, expressed as cumulative 80 kN equivalent single-axle loads (ESALs)
$N(t)$	Cumulative ESALs at the end of design year t , Eq. (12) (ESALs)
p_a	Atmospheric pressure, 101.325 kPa
RD	Subgrade rut depth (mm)
S	Degree of saturation (%)
t	Design year (years)
T	Design life, $T = 20$ years
$x_i, \Delta x_i$	Baseline value and perturbation of input i in Eq. (14)
α	van Genuchten fitting parameter (kPa^{-1})
β	Shape exponent of the permanent strain model (dimensionless)
ΔRD_i	Change in year-20 rut depth due to perturbation of input i (mm)
$\varepsilon_0, \varepsilon_{0,\text{ref}}$	Asymptotic permanent strain and its value at ψ_{ref} (dimensionless)
ε_p	Permanent (plastic) strain (dimensionless)
θ	Volumetric water content (m^3/m^3)
θ_r, θ_s	Residual and saturated volumetric water content (m^3/m^3)
θ_b	Bulk stress (kPa)
ρ, ρ_{ref}	Cycle-scaling parameter of the permanent strain model and its value at ψ_{ref} (dimensionless)
τ_{oct}	Octahedral shear stress (kPa)
ψ	Matric suction (kPa)
$\psi_0, \psi_{\text{end}}$	Baseline (year-1) and prescribed year-20 design suction (kPa)
$\psi_{\text{cap}}, \psi_{\text{eff}}$	Suction cap and effective suction in Eq. (7) (kPa)
$\psi_{\text{des}}(t)$	Critical (post-rainfall) design suction in design year t (kPa)
ψ_r	Fredlund-Xing residual suction (kPa)
ψ_{ref}	Reference suction for permanent deformation scaling, 200 kPa

2. Critical Review of Related Work

The work relevant to this study falls into three lines that have developed largely independently: suction-dependent characterisation of subgrade stiffness and permanent deformation; numerical modelling of moisture movement and deformation under pavements; and climate-projection-driven pavement performance analysis. Each line is assessed below in terms of what it establishes and what it does not deliver, rather than summarised study by study.

The first line is the strongest in experimental terms and provides the constitutive basis of the present framework. Suction-controlled repeated-load triaxial testing has repeatedly shown that the resilient modulus of compacted fine-grained and sandy subgrade soils increases nonlinearly with matric suction, and has produced the functional forms used in design practice [2], [9], [19]. Zhang et al. [20] and Qian et al. [11] extended this to the joint influence of compaction state and capillary saturation; Lim et al. [8] measured the influence of matric suction on both resilient modulus and California Bearing Ratio (CBR) of a compacted clay; Abdollahi and Vahedifard [10] added water content, temperature and hydraulic hysteresis to the prediction of resilient modulus; Luan and Han [21] proposed a multi-factor dynamic resilient modulus model for a modified unsaturated subgrade; and Chu [1] reviewed the resilient response of unsaturated subgrade soils. On the deformation side, Chu et al. [6] measured the permanent deformation of unsaturated subgrade soils under cyclic loading and showed its dependence on moisture state, stress level and number of cycles, while Everton and Erlingsson characterised permanent deformation under seasonal moisture variation and resilient behaviour under suction-controlled testing [7], [19]. The critical limitation of this line is that it is element-scale and either steady-state or single-season: it supplies measured suction dependence, but not a suction trajectory over a design life. It is also, and this is decisive for the present study, precisely the class of measured data against which a framework such as the one proposed here must eventually be calibrated and validated (Section 5).

The second line moves to the structural scale. Karumanchi et al. [22] evaluated numerically the effects of matric suction and groundwater-table variation on

long-term pavement subgrade performance, showing that a deeper water table raises suction, cohesion and modulus, and that infiltration through the pavement surface destroys that equilibrium and accelerates deformation. Permanent-deformation formulations for unbound layers [23], [24] and their evaluation against accelerated pavement testing (APT) [17], together with data-driven prediction of permanent strain [18], show that the deformation models themselves are mature. What this line does not do is impose an external, time-dependent climate forcing: the moisture boundary condition is prescribed as a water table depth, an infiltration event or a season, so the outputs are not referenced to a design-life performance criterion under a changing climate, and the wetting and drying branches of the process are not separated.

The third line couples climate projections to pavement performance. Mendoza-Sanchez et al. [16] developed a practical tool that transfers climate and climate-change information into the subgrade resilient modulus used for road pavement design, and Hosseini et al. [12] examined the mutual interaction between a changing climate and flexible pavement performance including resilience aspects. Swarna et al. quantified climate-change impacts on pavement performance and evaluated adaptation strategies [13], [25]; Sias et al. [14] synthesised climate impacts on roadways; and Zhang et al. [26], Yao et al. [27] and Zhang et al. [28] addressed pavement infrastructure ageing, adaptive maintenance and the regional variation of climate-driven rutting. This is the only line that carries emission scenarios explicitly, but its moisture pathway is coarse. Climate is transferred either through an aggregated index such as the TMI and an environmental factor [5], [16], or as a bulk moisture input to a performance model. Matric suction is therefore not an explicit state variable, the drying and wetting branches are not distinguished, and the correction is applied to stiffness rather than propagated into the rutting model.

Taken together, the three lines leave a specific methodological gap. Measured suction dependence exists but is not projected forward in time; numerical models resolve moisture but are not climate-forced; climate-driven studies carry scenarios but represent moisture as an index. To the authors' knowledge no published study propagates an explicit design-suction

trajectory through an SWCC model, a suction-dependent resilient modulus model and a moisture-scaled permanent deformation model in a single traceable chain, and then decomposes the resulting rut depth into its climate and model-parameter contributions. The present study fills that gap, and it fills it with prescribed suction pathways and representative parameters. Its contribution is therefore a transparent mechanism and a sensitivity ranking that indicates where measurement effort should be directed; it is not a validated forecast, and the studies of the first line above remain the source of the measured data required for calibration.

3. Proposed Methodology

The proposed framework couples four physically-based models into a unified simulation pipeline: an SWCC model defines the moisture-suction relationship; a suction-dependent resilient modulus model captures stiffness response; a permanent deformation model predicts rutting accumulation; and a dual-suction climate module propagates the prescribed design-suction pathway through the design life, with traffic loading expressed via the AASHTO ESAL growth model. Two properties of the input set must be stated before the equations, because they condition every result in Section 4. First, no measured dataset is used: each soil, traffic and pathway parameter are a representative value taken or inferred from published work for an arid sandy-clay subgrade, and none has been calibrated against, or validated with, measurements on a specific soil or site. Second, the climate-analogue suction pathways are assumed scenario parameters and not climate model output, as set out in Section 3.4.

3.1. Soil-Water Characteristic Curve (SWCC) modeling

The unsaturated hydraulic response of the subgrade soil is characterized with two independent SWCC formulations, which are applied in parallel as a check of internal consistency between two mathematical descriptions of the same assumed curve. The van Genuchten [29] closed-form equation, Equation (1), relates the volumetric water content θ (m^3/m^3) to the matric suction ψ (kPa) through the residual volumetric

water content θ_r (m^3/m^3), the saturated volumetric water content θ_s (m^3/m^3), the fitting parameter α (kPa^{-1}) and the dimensionless curve-shape parameter n ; the dimensionless auxiliary exponent m is given by Equation (2) [29]:

$$\theta(\psi) = \theta_r + (\theta_s - \theta_r) \times [1 + (\alpha\psi)^n]^{-m} \quad (1)$$

$$m = 1 - \frac{1}{n} \quad (2)$$

As a cross-check, the Fredlund and Xing [30] model, Equations (3) and (4), is applied, in which $C(\psi)$ is a dimensionless correction factor that forces the water content to zero at $\psi = 10^6$ kPa, ψ_r (kPa) is the residual suction, a (kPa) is a fitting parameter related to the air-entry value, n and m are the dimensionless Fredlund-Xing curve-shape parameters (distinct from the van Genuchten n and m), and e is the base of the natural logarithm [30]:

$$C(\psi) = 1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)} \quad (3)$$

$$\theta(\psi) = C(\psi) \times \frac{\theta_s}{\left\{\ln\left[e + \left(\frac{\psi}{a}\right)^n\right]\right\}^m} \quad (4)$$

The degree of saturation S (dimensionless, reported in %) is then derived as [31]:

$$S(\psi) = \frac{\theta(\psi) - \theta_r}{\theta_s - \theta_r} \quad (5)$$

No measured SWCC data were used. The parameters ($\theta_r = 0.040$, $\theta_s = 0.380$, $\alpha = 0.008 \text{ kPa}^{-1}$, $n = 1.65$ for van Genuchten; $a = 120 \text{ kPa}$, $n = 1.80$, $m = 0.75$, $\psi_r = 3000 \text{ kPa}$ for Fredlund & Xing [30]) are representative values chosen to reproduce the shape of a typical dry sandy-clay subgrade curve. They are explicitly representative, or artificial, parameters: they are not experimentally calibrated soil parameters, and they are not claimed to describe any particular soil. It follows that the close agreement between the two formulations reported in Section 4.1 demonstrates model consistency, or inter-

model comparison, and is not evidence of physical validity; two mathematical expressions evaluated with mutually consistent assumed parameters must agree. Physical validation requires independently measured retention data on the soil concerned, for example by pressure plate, chilled-mirror hygrometer or filter paper over the same suction range, and that requirement is stated in Section 5. The suction range is sampled logarithmically from 0.1 to 10^5 kPa (800 points) to capture both the air-entry and the residual-saturation portions of the curve.

Both formulations are used here in a single-branch, monotonic drying form, so hysteresis of the retention curve is not represented. This simplification has a known direction of error and is therefore stated rather than left implicit. For a given suction the wetting branch lies below the drying branch, so the water content reached on re-wetting after a dry period is lower than the drying-branch value, and the suction corresponding to a given post-rainfall water content is correspondingly higher [31], [32].

Because the present study advances a drying annual-average state and separately imposes a wetted post-rainfall state, using a single drying branch over-estimates the water content of the wetted state and under-estimates its suction; the computed stiffness loss and rut depth are therefore conservative, that is larger, rather than optimistic. Hysteresis is omitted because its calibration requires paired drying and wetting measurements on the same soil, which do not exist for a representative parameter set. Abdollahi and Vahedifard [10] show that including hydraulic hysteresis measurably changes the predicted resilient modulus of unsaturated subgrade soils. Table 1 presents soil-water characteristic curve (SWCC) modeling.

3.2. Suction-dependent resilient modulus

Subgrade stiffness is described by a modified MEPDG-type resilient modulus (M_r , MPa) equation that includes matric suction, based on Yang et al. [2] and the MEPDG formulation [4]. The model augments the typical k_1 - k_2 - k_3 bulk-stress form with a fourth constant k_4 that controls the suction sensitivity:

Table 1. Soil-Water Characteristic Curve (SWCC) Modeling.

Parameter / Quantity	Symbol	Value	Unit	Description
Residual water content	θ_r	0.040	—	van Genuchten / Fredlund-Xing
Saturated water content	θ_s	0.380	—	van Genuchten / Fredlund-Xing
van Genuchten fitting parameter	α	0.008	kPa ⁻¹	Air-entry related parameter
van Genuchten curve shape	n	1.65	—	van Genuchten model
Fredlund-Xing parameter	a	120.0	kPa	Approx. air-entry value
Fredlund-Xing curve shape	n	1.80	—	Fredlund-Xing model
Fredlund-Xing curve shape	m	0.75	—	Fredlund-Xing model
Fredlund-Xing residual suction	ψ_r	3000.0	kPa	Correction factor $C(\psi)$
Suction sampling range	ψ	0.1 – 10 ⁵	kPa	800 log-spaced points
Governing equations	—	Eq. (1)–(5)	—	$\theta(\psi)$, m , $C(\psi)$, $S(\psi)$
Output	$\theta(\psi)$, $S(\psi)$	—	%, %	Water content & saturation curves
Dataset used	—	None	—	Representative (artificial) parameters, not measured

Table 2. Suction-Dependent Resilient Modulus.

$$M_r(\theta_b, \tau_{oct}, \psi) = k_1 \times p_a \times \left(\frac{\theta_b}{p_a} + 1 \right)^{k_2} \times \left(\frac{\tau_{oct}}{p_a} + 1 \right)^{k_3} \times \exp \left(k_4 \times \frac{\psi_{eff}}{p_a} \right) \quad (6)$$

where the bulk stress θ_b (kPa) and the octahedral shear stress τ_{oct} (kPa) define the stress state, $p_a = 101.325$ kPa is the atmospheric pressure used for normalisation, k_1 to k_4 are dimensionless regression constants, and the effective suction ψ_{eff} (kPa) is limited by the suction cap ψ_{cap} (kPa) to avoid non-physical exponential blow-up at very dry conditions [9]:

$$\psi_{eff} = \min(\psi, \psi_{cap}) \quad (7)$$

The regression constants used here ($k_1 = 250$, $k_2 = 0.55$, $k_3 = -0.35$, $k_4 = 0.15$, $\psi_{cap} = 1000$ kPa) are assumed, not fitted: no triaxial dataset was available for the modelled soil, and the constants were selected so that the resulting relationship spans a plausible saturated-to-unsaturated stiffness range (≈ 31 MPa at saturation to ≈ 138 MPa at the suction cap) and reproduces the shape of the M_r -suction relationships reported from suction-controlled testing [2], [9], [19]. They are therefore synthetic coefficients and the stiffness values that follow from them are model outputs, not measured properties. Three representative stress states (low, mid, high) covering typical subgrade loading conditions are evaluated to expose stress-state sensitivity.

Parameter / Quantity	Symbol	Value	Unit	Description
Regression constant	k_1	250	—	MEPDG bulk-stress coefficient
Regression constant	k_2	0.55	—	Bulk stress exponent
Regression constant	k_3	-0.35	—	Octahedral shear stress exponent
Suction sensitivity constant	k_4	0.15	—	Yang et al. [2] extension
Atmospheric pressure	p_a	101.325	kPa	Normalization constant
Suction cap	ψ_{cap}	1000.0	kPa	Prevents exponential blow-up
Bulk stress (reference)	θ_b	60.0	kPa	Reference stress state
Octahedral shear stress (reference)	τ_{oct}	12.0	kPa	Reference stress state
Stress states evaluated	—	Low / Mid / High	—	30/6, 60/12, 90/18 kPa
Resilient modulus range	M_r	$\approx 31 - 138$	MPa	Saturation to suction cap
Governing equations	—	Eq. (6)–(7)	—	$M_r(\theta_b, \tau_{oct}, \psi)$, ψ_{eff}
Dataset used	—	None	—	Synthetic coefficients, not calibrated on the modelled soil

Two consequences of this adopted standard are stated explicitly. First, because the coefficients were not regressed on measurements from the modelled soil, the computed relationship is compared in Section 4.3 with the trends and magnitudes reported from suction-controlled laboratory testing [2], [8], [9], [19]; that comparison is an order-of-magnitude plausibility check and not a calibration, and no goodness-of-fit statistic can legitimately be reported for it. Second, k_4 is the only suction-dependent term and the suction cap $\psi_{\text{cap}} = 1000$ kPa is a numerical device that bounds an otherwise unbounded exponential; it has no physical meaning, and the model is not admissible beyond that cap. The suction range that actually governs the results of this study (55-280 kPa) lies well inside the cap. Finally, suction-dependent resilient modulus is presented in Table 2.

3.3. Permanent deformation and cumulative traffic loading

Rutting accumulation is modeled using the Tseng and Lytton shakedown-based permanent strain formulation, expressing the dimensionless permanent (plastic) strain ε_p as an asymptotic exponential function of the number of load repetitions N , where N is the cumulative number of 80 kN ESAL applications given by Equation (12) and is therefore expressed in ESALs [33]:

$$\varepsilon_p(N) = \varepsilon_0 \times \exp\left(-\frac{\rho}{N^\beta}\right) \quad (8)$$

where ε_0 is the dimensionless asymptotic permanent strain, ρ is the dimensionless cycle-scaling parameter and β is the dimensionless shape exponent; ε_0 and ρ are moisture dependent and are scaled with the design suction ψ (kPa) relative to a reference state ($\psi_{\text{ref}} = 200$ kPa, $\varepsilon_{0,\text{ref}} = 0.018$, $\rho_{\text{ref}} = 85.0$), whereas $\beta = 0.35$ is held constant [23], [24], [33]:

$$\varepsilon_0(\psi) = \varepsilon_{0,\text{ref}} \times \left(\frac{\psi_{\text{ref}}}{\psi}\right)^{0.65} \quad (9)$$

$$\rho(\psi) = \rho_{\text{ref}} \times \left(\frac{\psi}{\psi_{\text{ref}}}\right)^{0.50} \quad (10)$$

The subgrade rut depth RD (mm) is obtained by multiplying the permanent strain by the subgrade layer thickness h (m), the factor 1000 converting metres to millimetres:

$$\text{RD}(N) = \varepsilon_p(N) \times h \times 1000 \quad (11)$$

Cumulative traffic loading is modeled using the AASHTO ESAL growth function with an initial Average Annual Daily Truck Traffic (AADTT) of $\text{AADTT}_0 = 1000$ trucks/day, an annual growth rate $g = 3.5\%$ ($g = 0.035$ in Equation (12)) and a truck factor of 1.75 ESALs/truck, compounded over the design years $i = 1, \dots, t$ of the 20-year design life ($T = 20$ years) to give the cumulative number of ESALs, $N(t)$ [3]:

$$N(t) = \sum_{i=1}^t \text{AADTT}_0 \times 365 \times (1 + g)^i \times 1.75 \quad (12)$$

The provenance of each deformation parameter is stated here, because the rut depths in Section 4 follow directly from them. The functional form of Equation (8) is that of Tseng and Lytton [33] as implemented for unbound layers [17], [23], [24]. The reference values $\varepsilon_{0,\text{ref}} = 0.018$ and $\rho_{\text{ref}} = 85.0$ at $\psi_{\text{ref}} = 200$ kPa, the scaling exponents 0.65 and 0.50 in Equations (9) and (10), and the exponent $\beta = 0.35$ are all assumed. They were not regressed from measurements on the modelled soil; they were selected so that the model reproduces the qualitative behaviour reported for moisture-dependent permanent deformation of unsaturated subgrade soils, namely a higher asymptotic strain and a smaller cycle-scaling parameter as suction decreases [6], [7], [17], [23], [24], and so that the baseline case remains within the range of measured design-life rutting for a competent subgrade. No independent verification of these coefficients was performed, and their applicable soil and stress range is therefore undefined. Consequently, the deformation results of Section 4 are reported as scenario model outputs and not as verified predictions, and β and the ε_0 and ρ scalings are carried into the sensitivity analysis of Section 3.4.

The 20 mm rut depth used throughout this paper is an adopted analysis threshold and not a documented universal AASHTO failure criterion; the earlier presentation of it as such was incorrect. The 1993 AASHTO guide defines failure through loss of serviceability, expressed as a terminal Present Serviceability Index (PSI), rather than through a permissible rut depth [3]. The MEPDG applies rutting

limits to total permanent deformation of the pavement structure as agency-selected performance criteria evaluated at a chosen reliability, so the numerical limit is set by the implementing agency and is not fixed by the guide itself [4]. Values of the order of 12-25 mm of total rutting are commonly adopted in agency practice, and 20 mm is used here as one representative reference line so that the pathways can be compared against a fixed value. It is applied to the subgrade contribution alone, which is conservative in one respect, since subgrade rutting is only part of total surface rutting, and unconservative in another, since the asphalt and base contributions are not modelled. No claim is made that crossing this line constitutes failure under any particular specification.

Equation (12) is reported in full so that the traffic input is reproducible. $AADTT_0 = 1000$ trucks/day is the initial AADTT assigned to the design lane in year 0; $g = 3.5\%/yr$ is the compound annual growth rate; and 1.75 is the truck factor in equivalent single-axle loads per truck, which converts trucks directly into 80 kN equivalent single-axle load applications. The output $N(t)$ is therefore

the cumulative number of equivalent single-axle load applications up to the end of design year t , expressed in ESALs; the same symbol N , with the same unit, denotes the number of load repetitions in Equations (8) and (11) and on the horizontal axes of Figures 4 and 5. It is neither a number of trucks nor a number of physical axles.

Two further conventions are made explicit: all trucks are assigned to the design lane, so no lane-distribution or directional factor is applied, and the axle-load spectrum is collapsed into the single truck factor rather than resolved axle by axle. For year 1, $N(1) = 1000 \times 365 \times 1.035 \times 1.75 = 6.61 \times 10^5$ ESALs; summing the geometric series over the design life gives $N(20) = 1000 \times 365 \times 1.75 \times [(1.035^{21} - 1.035)/0.035] = 1.87 \times 10^7$ ESALs. The year-by-year values are listed in Appendix A together with the corresponding design suction and rut depth. No traffic count data were used; $AADTT_0$, g and the truck factor are representative values for a busy arterial road. The permanent deformation and cumulative traffic loading are shown in Table 3.

Table 3. Permanent deformation and cumulative traffic loading.

Parameter / Quantity	Symbol	Value	Unit	Description
Reference strain coefficient	$\varepsilon_{0,ref}$	0.018	—	Tseng-Lytton scaling reference
Reference rho parameter	ρ_{ref}	85.0	—	Tseng-Lytton scaling reference
Permanent strain exponent	β	0.35	—	Assumed value (Section 3.3)
Suction scaling exponents	—	0.65 / 0.50	—	Assumed exponents of Eqs. (9) and (10)
Reference design suction	ψ_{ref}	200.0	kPa	Permanent deformation parameter scaling
Subgrade layer thickness	h	0.60	m	Rut depth scaling
Initial truck traffic	$AADTT_0$	1000	trucks/day	Busy arterial road
Annual traffic growth rate	g	3.5	%/yr	ESAL growth model
Truck factor	—	1.75	ESALs/truck	AASHTO conversion
Design life	T	20	years	Analysis horizon
Adopted rut-depth threshold	RD	20	mm	Analysis threshold, not an AASHTO criterion (Section 3.3)
Governing equations	—	Eq. (8)–(12)	—	$\varepsilon_p(N)$, $\varepsilon_0(\psi)$, $\rho(\psi)$, $RD(N)$, $N(t)$
Dataset used	—	None	—	Representative values; no traffic count data

3.4. Climate-forced suction projection and sensitivity analysis

Climate change is accounted for by a two-suction framework in which the annual-average soil condition follows a drying trend while the critical state that follows a rainfall event becomes progressively wetter. The second state governs design, because it is the state in which stiffness is lowest. Two end-member pathways are constructed by linear interpolation of the critical design suction ψ_{des} from its baseline value of 280 kPa to prescribed end-of-year-20 values of 140 kPa and 55 kPa, which are labelled the Shared Socioeconomic Pathway (SSP) SSP2-4.5 and SSP5-8.5 analogues:

$$\psi_{\text{des}}(t) = \psi_0 - (\psi_0 - \psi_{\text{end}}) \times \frac{t - 1}{T - 1} \quad (13)$$

where $\psi_{\text{des}}(t)$ (kPa) is the critical design suction in design year t ($t = 1, \dots, T$), $\psi_0 = 280$ kPa is the baseline (year-1) design suction, ψ_{end} (kPa) is the prescribed year-20 suction of the pathway (140 kPa or 55 kPa) and $T = 20$ years is the design life. The time series is passed forward in Equations (6)-(12) once per year to create resilient modulus and rut depth time histories for a given pathway.

The relationship between the emission scenarios and these numbers requires an explicit statement, because it is the principal assumption of the paper and it was described imprecisely in the earlier version. SSP2-4.5 and SSP5-8.5 are climatic and emission scenarios [34], [35]; they are not soil-water scenarios, and they do not prescribe a value of matric suction. The pathways of Equation (13) were obtained by prescribing the end-of-life suction directly, that is by defining the endpoint rather than deriving it from a climate projection. They are accordingly labelled here as SSP-analogue pathways: artificially constructed, hypothetical suction trajectories whose direction, a wetter critical state under the higher-emission label as a consequence of intensified extreme precipitation, and whose relative ordering are qualitatively consistent with the intensification of heavy precipitation and the drying of mean soil moisture projected for arid regions in the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) [15], but whose magnitudes are assumed. They are not derived from Coupled Model

Intercomparison Project Phase 6 (CMIP6) output, they are not downscaled, and no observational or reanalysis dataset is used. Every statement about SSP5-8.5 or SSP2-4.5 in Section 4 should be read as a statement about the assumed pathway carrying that label, and not as a climate projection. Deriving these pathways physically, rather than assuming them, would require the following verifiable sequence, which lies outside the scope of the present modelling study and is stated as the required next step: selection of a downscaled and bias-corrected CMIP6 ensemble for the site under each SSP [34], [35]; extraction of daily precipitation and temperature, including extreme-precipitation statistics rather than monthly means; a soil-water balance driven by that series, resolving infiltration, redistribution, evaporation and drainage with unsaturated hydraulic conductivity under the pavement and shoulder boundary conditions; conversion of the resulting profile of volumetric water content into matric suction through a measured retention curve including its wetting branch; and extraction of the annual-average and post-storm critical suction from that time series, with the ensemble spread carried forward as an uncertainty band. Only the last two steps of that chain are represented in the present framework, and they are represented with assumed parameters. Table 4 states, quantity by quantity, which values follow from the physics of the framework and which are assumed scenario parameters.

The post-rainfall suction is likewise not determined by a rainfall amount alone, and the assumptions behind the single value used for each pathway are therefore listed. For a given storm the suction reached at subgrade level depends on rainfall intensity and duration, antecedent moisture, the infiltration capacity and unsaturated hydraulic conductivity of the pavement and subgrade materials, the drainage condition, subsequent evaporation, the depth of the point considered, and the retention curve itself including its hysteresis. None of these is resolved here. Instead, the wetted state is treated as instantaneous and fully developed at the top of a 0.6 m subgrade layer with no depth profile; infiltration and drainage are not modelled; no recovery of suction between storms is credited within the design year; and the critical state is applied to the whole of the year for which it is defined. ssumed pathway.

Table 4. Climate-forced suction projection and sensitivity analysis.

Parameter / Quantity	Symbol	Value	Unit	Description
Baseline design suction	ψ_0	280.0	kPa	Year-1 critical condition
SSP2-4.5 terminal suction (yr 20)	ψ_{end}	140.0	kPa	Moderate emissions scenario
SSP5-8.5 terminal suction (yr 20)	ψ_{end}	55.0	kPa	High emissions scenario
Climate pathways modeled	—	SSP2-4.5 / SSP5-8.5 analogues	—	Assumed analogue labels, not CMIP6-derived
Sensitivity perturbation range	—	$\pm 20 - 50$	%	Tornado analysis
Parameters perturbed	—	7 inputs	—	ψ , ε_0 , ρ , β , h , AADTT, pathway (local screening)
Dominant sensitivity driver	—	Assumed pathway shift	—	Baseline $\rightarrow$ SSP5-8.5 analogue (+15.5 mm)
Governing equations	—	Eq. (13)–(14)	—	$\psi_{\text{des}}(t)$, ΔRD_i
Dataset used	—	None	—	Suction endpoints prescribed (Section 3.4)

Table 5. Classification of framework quantities: derived within the model versus assumed scenario parameters.

Quantity	Status in this study	Basis / provenance
$\theta(\psi)$ and $S(\psi)$ curves	Derived within the framework, Eqs. (1)–(5)	Computed from the assumed SWCC parameters
SWCC parameters θ_r , θ_s , α , n , a , m , ψ_r	Assumed (representative / artificial)	Selected for a typical dry sandy-clay; not measured
SWCC hysteresis	Not represented	Single drying branch; direction of error stated in Section 3.1
$M_r(\theta_b, \tau_{\text{oct}}, \psi)$	Derived within the framework, Eq. (6)	Functional form from suction-controlled testing [2]
M_r coefficients k_1 – k_4 , ψ_{cap}	Assumed (synthetic)	Literature-consistent magnitudes; not regressed on the modelled soil
$\varepsilon_p(N)$ and $RD(N)$	Derived within the framework, Eqs. (8)–(11)	Computed from the assumed deformation parameters
$\varepsilon_{0,\text{ref}}$, ρ_{ref} , exponents 0.65 / 0.50, β	Assumed (synthetic)	Chosen to reproduce published moisture-deformation trends [6], [7], [17], [23], [24]
Cumulative ESALs $N(t)$	Derived within the framework, Eq. (12)	Closed-form geometric series; worked example in Section 3.3
AADTT ₀ , growth rate g , truck factor	Assumed	Representative busy-arterial values; no traffic counts used
Design-suction pathway $\psi_{\text{des}}(t)$	Assumed scenario parameter	Endpoints prescribed (280 $\rightarrow$ 140 / 55 kPa); not derived from CMIP6
Annual-average (drying) suction band	Assumed scenario parameter	900–1500 kPa, representative arid range
Labels SSP2-4.5 / SSP5-8.5	Assumed analogue labels	Direction and ordering only, consistent with IPCC AR6 [15]
20 mm rut-depth threshold	Adopted analysis threshold	Agency-practice value; not an AASHTO failure criterion [3], [4]
Sensitivity rankings (Fig. 7)	Derived within the framework, Eq. (14)	Local one-at-a-time screening, conditional on all rows above

The last assumption is conservative, because a real wetted critical state persists for only part of a year, and it is one reason why the computed rut depths should be read as upper estimates under the a

Seven inputs were perturbed one at a time to rank their influence on the year-20 rut depth: the climate pathway, the design suction, the ε_0 scaling, the ρ scaling, the β exponent, the subgrade thickness and the AADTT. Perturbations of ± 20 –50% about the baseline values were

applied, and the associated change in year-20 rut depth was computed with Equation (14), in which ΔRD_i (mm) is the change in year-20 rut depth caused by input i , x_i is the baseline value of input i , Δx_i is its perturbation, and $RD(x_{\text{baseline}})$ (mm) is the year-20 rut depth with all inputs at their baseline values:

$$\Delta RD_i = RD(x_i \pm \Delta x_i) - RD(x_{\text{baseline}}) \quad (14)$$

Table 5 classifies every quantity in the framework as either derived within the model or assumed, so that the two categories cannot be confused when the results are read.

4. Results and Discussion

The simulation results of the coupled SWCC–resilient modulus–permanent deformation model is demonstrated for an illustrative dry sandy-clay subgrade over a 20-year design period in this section. The van Genuchten [29] and Fredlund-Xing [30] SWCC models are paired with a suction-based MEPDG resilient modulus equation and the Tseng-Lytton permanent deformation model. The AASHTO ESAL traffic loading along with the two assumed SSP-analogue suction pathways labelled SSP2-4.5 and SSP5-8.5 (Section 3.4) and a no-change baseline are used to drive the performance analysis. The subsections are grouped by related factors and cover soil-water characteristic, resilient modulus degradation, permanent deformation (rutting) evolution, and parameter sensitivity analyses, with the adopted 20 mm rut-depth threshold (Section 3.3) for comparison throughout. All numerical values reported in this section were recomputed directly from Equations (1)-(14) with the parameters of Tables 1-4, so that every figure and every number can be reproduced from the manuscript alone; where a value differs slightly from the earlier version of this work, the value given here is the one consistent with the stated equations that have been redrawn accordingly. Because the parameter set is assumed rather than measured, values are quoted to 0.1 mm for traceability only, and the associated uncertainty is quantified explicitly in Sections 4.6 and 4.7 rather than implied by the number of digits reported.

4.1. Soil-water characteristic curve behavior

Figure 1 shows the SWCC as predicted by the van Genuchten [29] and Fredlund & Xing [30] equations for the arid sandy-clay subgrade. The two equations agree closely over the entire suction range (0.1–10⁵ kPa), which confirms that the two formulations were parameterised consistently; as explained in Section 3.1 this is an inter-model consistency check and not a validation of either curve against measurement.

The curve has the expected three-stage response of an unsaturated soil, with a nearly saturated plateau at $\theta \approx \theta_s = 38\%$ for suctions up to about 10 kPa, a steep desaturation region from about 50 to 10⁴ kPa corresponding to the air-entry and primary drainage region, and a residual zone above 10⁴ kPa in which the water content approaches $\theta_r = 4\%$ asymptotically. The two equations differ only in the residual zone ($\psi > 10^4$ kPa), where the Fredlund & Xing [30] model predicts slightly lower water contents because of the explicit correction factor that forces zero water content at $\psi = 10^6$ kPa, while the van Genuchten [29] model retains a small residual tail. The design suction range used in this study (55–280 kPa, Section 3.4) lies within the steep desaturation branch, where a small change in suction produces a large change in water content. That position on the curve, and not the climate assumption itself, is the mechanism by which the imposed post-rainfall suction changes are amplified into large changes in degree of saturation, and hence into the modulus reduction and rut-depth increase reported in the following sections.

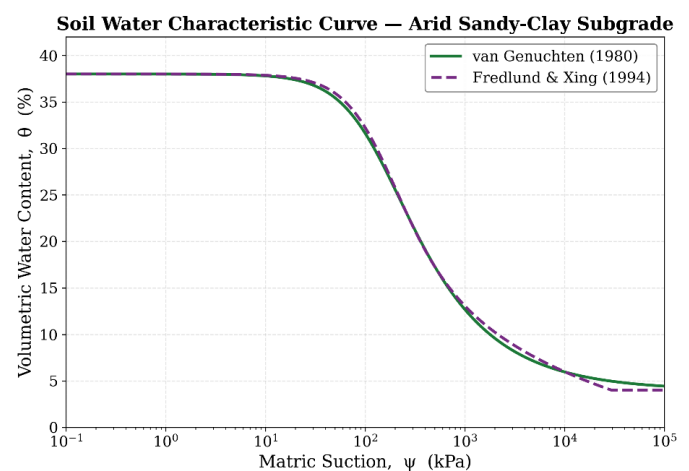


Figure 1. Soil-Water characteristic curves: model comparison.

4.2. Degree of saturation and climate design ranges

Figure 2 is the same data as in Figure 1, but expressed here as the degree of saturation, S , and the two climate-relevant suction bands from Section 3.4 are also plotted. The two models again fit very well and the same general trend is observed; saturation is at near 100% for suctions below 10 kPa, through a strong transition zone to below 10% for suctions above 10^4 kPa.

A clear asymmetry is evident in the hydrological response of the assumed soil. The design range of post-rainfall suction (light blue band, 55-280 kPa) falls on the steepest part of the desaturation curve, where the computed degree of saturation changes from about 91% to about 54%, whereas the annual-average dry range (orange band, 900-1500 kPa) lies on the lower, much flatter part of the curve, where saturation is low and varies only between about 20% and 27%. This is the physical basis of the two-suction treatment: the design-determining changes in saturation are produced by episodic post-rainfall wetting acting in the sensitive region of the retention curve, while a year-long drying trend of comparable suction magnitude produces only a small change in saturation. The prescribed post-rainfall endpoints of 140 kPa and 55 kPa therefore correspond to computed saturations of about 73% and 91% respectively, and it is this increase in saturation, imposed as an assumption rather than derived from a climate model, that drives the modulus loss and the additional permanent deformation reported in Sections 4.3 to 4.6.

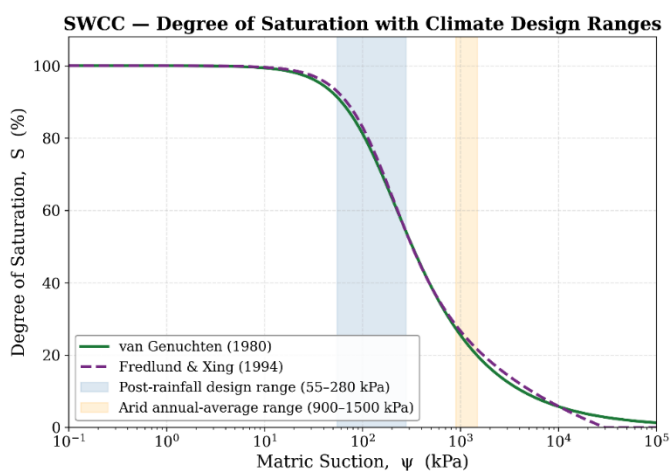


Figure 2. Degree of saturation with design ranges.

4.3. Resilient modulus sensitivity to suction and stress state

The estimated M_r over the entire suction range for three representative stress states is shown in Figure 3, with the three pathway design points at the intermediate stress state highlighted. M_r rises monotonically and nonlinearly with suction at all stress states, from about 29-34 MPa at near-zero suction to 125-149 MPa at the suction cap of 1000 kPa, which is consistent with the stiffening influence of capillary bonding in unsaturated soils. The stress-state dependence is also visible: for a given suction the high stress state ($\theta_b = 90$ kPa, $\tau_{oct} = 18$ kPa) plots above the low stress state, which is the stress-hardening effect of the k_2 and k_3 exponents.

The baseline design point ($\psi = 280$ kPa) gives $M_r \approx 47.6$ MPa. The SSP2-4.5 analogue ($\psi = 140$ kPa) and the SSP5-8.5 analogue ($\psi = 55$ kPa) fall on the lower, flatter part of the M_r - ψ curve, with moduli of about 38.7 MPa and 34.1 MPa respectively, that is reductions of 19% and 28% relative to baseline. Because these points lie in the low-suction region where the slope of the M_r - ψ relationship is smallest, the stiffness response flattens, and further suction loss beyond the SSP5-8.5 analogue endpoint would produce comparatively little additional stiffness loss.

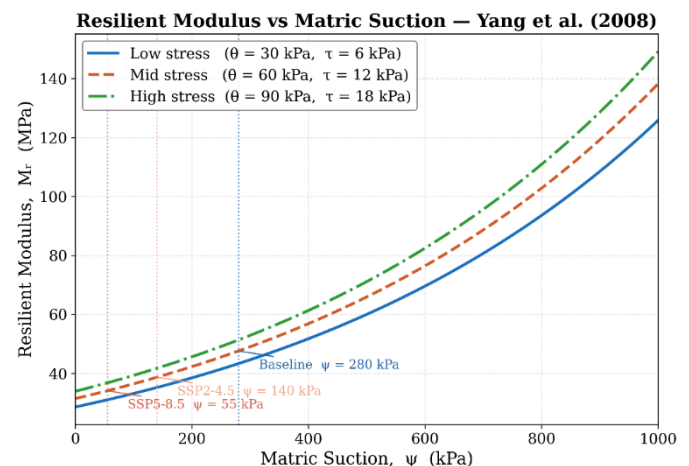


Figure 3. Resilient modulus versus matric suction.

Because the k -coefficients are assumed rather than fitted, the computed relationship is placed against published suction-controlled measurements as a plausibility check. Suction-controlled repeated-load triaxial testing on compacted subgrade soils [2], suction-controlled testing on unsaturated sandy soils [19], the

suction-based resilient modulus framework of Cary and Zapata [9] and the measurements of Lim et al. [8] on a compacted clay all display the two features reproduced in Figure 3: a monotonic and concave increase of resilient modulus with matric suction, and moduli for compacted fine-grained subgrades that remain within the tens to low hundreds of MPa over the suction range relevant to pavement design. The computed range of about 31-138 MPa between saturation and the 1000 kPa cap is consistent with that envelope in both magnitude and shape. This comparison is qualitative and trend-level only. It is not a validation: no measured M_r -suction pair for the modelled soil is reproduced, no goodness-of-fit statistic is reported, and the coefficients were not obtained by regression on such data. The measurement programme that would close this gap is specified in Section 5.

4.4. Permanent strain accumulation under the assumed suction pathways

Accumulation of permanent strain (ϵ_p) with cumulative traffic N (ESALs) for the three pathways under the Tseng-Lytton shakedown model is presented in Figure 4.

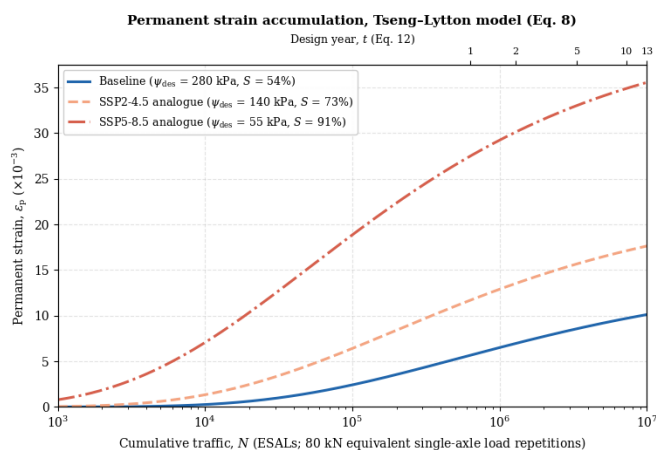


Figure 4. Permanent strain ϵ_p versus cumulative traffic N (ESALs) for the three suction pathways.

All three cases display the expected asymptotic exponential trend, with rapid growth in the early-cycle regime and a flattening towards the asymptote ϵ_0 at high cycle numbers. The separation between cases is substantial: at $N = 1 \times 10^7$ ESALs, which is the right-

hand end of the horizontal axis of Figure 4 and is reached at about design year 13 according to Equation (12) and Table A1, the computed ϵ_p is 10.1×10^{-3} for the baseline, 17.6×10^{-3} for the SSP2-4.5 analogue and 35.6×10^{-3} for the SSP5-8.5 analogue, the last being about 3.5 times the baseline value. This divergence is a direct and traceable consequence of the assumed moisture scalings of Equations (9) and (10) rather than an independent finding: a lower design suction raises the asymptotic strain coefficient ϵ_0 and lowers ρ , so the curve both rises higher and approaches its asymptote sooner. The practical implication is nevertheless worth stating, because it is a property of the model structure that would survive recalibration: under the wettest assumed pathway the strain exceeds the entire asymptotic value of the baseline case after only about 4×10^4 ESALs, so most of the additional damage is accumulated early in service rather than at the end of the design life. The widening of the gap between pathways as N increases likewise indicates that the effect of suction loss is multiplicative rather than additive in this formulation.

4.5. Rut depth progression and the adopted rut-depth threshold

Figure 5 expresses the same computation as physical rut depth against cumulative traffic and compares it with the 20 mm threshold adopted in Section 3.3. Under the baseline pathway the rut depth remains far below that line over the whole range, reaching 6.1 mm at $N = 1 \times 10^7$ ESALs.

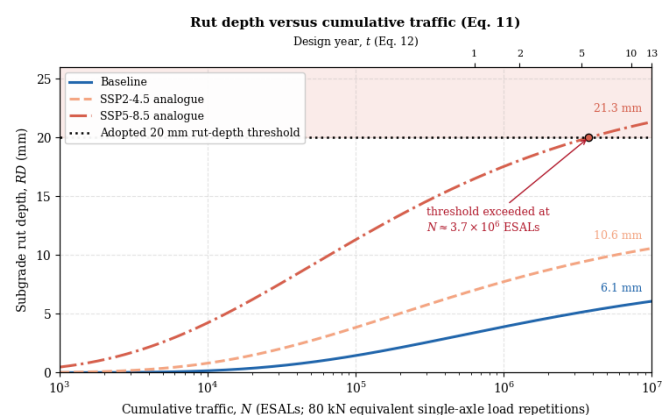


Figure 5. Subgrade rut depth RD versus cumulative traffic N (ESALs).

Under the SSP2-4.5 analogue the rut depth grows faster and reaches 10.6 mm at $N = 1 \times 10^7$ ESALs, which is below the adopted line but close to twice the baseline value. Under the SSP5-8.5 analogue the computed rut depth crosses the adopted 20 mm line at $N \approx 3.7 \times 10^6$ ESALs and continues to 21.3 mm at $N = 1 \times 10^7$ ESALs, that is about 7% above the threshold. Since the traffic model of Equation (12) accumulates $N = 1 \times 10^7$ ESALs by about design year 13 (Table A1), and $N(20) = 1.87 \times 10^7$ ESALs over the whole design life, the exceedance in this fixed-suction presentation occurs well within the nominal design life, and a section proportioned on the baseline design suction would lose the assumed serviceability margin before the end of that life. Two qualifications belong with this result. The rut depth compared with the line is the subgrade contribution alone, not total pavement rutting, and the curves of Figure 5 hold the suction at its end-of-life value for the whole loading history, which is why the exceedance appears earlier here than in the year-by-year simulation of Section 4.6. The shaded region above the line indicates the portion of the loading history spent beyond the adopted threshold under that pathway.

4.6. Rut depth progression across the 20-year design life

Figure 6 shows the evolution of rut depth over the 20-year design life when the time-varying suction pathways of Section 3.4 are used year by year, rather than the end-of-life suction being applied throughout.

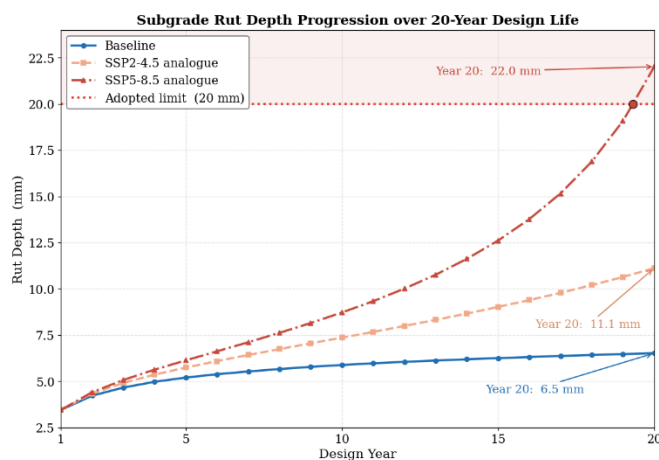


Figure 6. Rut depth over design life.

All three cases start from the same year-1 value of about 3.4 mm, since the pathways share the same initial suction. They then diverge. The baseline case grows slowly and almost linearly to 6.5 mm at year 20. The SSP2-4.5 analogue grows to 11.1 mm, close to twice the baseline value but below the adopted threshold throughout. The SSP5-8.5 analogue accelerates from about year 12 as its design suction falls towards 55 kPa, crosses the 20 mm line between years 19 and 20 (interpolated year 19.3) and reaches 22.0 mm at year 20. The shape of that curve is the practically relevant result: degradation is not linear in time, so a section proportioned on present-day suction would appear adequate for most of its life and lose its margin in the final few years, when the compounding of traffic and the assumed suction loss coincide.

The precision of these numbers must be read in the light of Section 3.3. Because $\varepsilon_{0,\text{ref}}$, ρ_{ref} , the scaling exponents and β are assumed, the year-20 value under the SSP5-8.5 analogue is better stated as of the order of 20 mm, with a parameter-perturbation range of about 12–31 mm obtained by combining the $\pm 30\%$ ε_0 , $\pm 30\%$ ρ and ± 0.05 β perturbations of Section 3.4. The crossing year carries a comparable uncertainty and is not a calendar prediction. What the model supports is a conditional and ordinal statement: under the assumed high-emission analogue the subgrade contribution to rutting reaches the adopted threshold within the 20-year horizon, whereas under the constant-climate baseline it reaches less than a third of it, and the ordering of the three pathways is robust to every perturbation examined. The phrase used in the earlier version of this work, that failure occurs in year 18–19, is replaced accordingly: what occurs between years 19 and 20 is the exceedance of a model threshold under an assumed pathway with assumed coefficients, not the failure of a real pavement.

4.7. Sensitivity analysis of rut depth drivers

The influence of the seven model inputs on the year-20 rut depth, obtained by one-at-a-time perturbation, is presented in Figure 7. The reference case for every bar is the constant-climate baseline pathway, whose year-20 rut depth is 6.5 mm. Replacing that pathway with the SSP5-8.5 analogue increases the year-20 rut depth by 15.5 mm, about three times the next largest effect; the

corresponding shift to the SSP2-4.5 analogue gives +4.6 mm. The second-ranked input is the design suction itself ($\pm 50\%$), at +4.6 mm and -1.8 mm, the asymmetry reflecting the nonlinearity of both the resilient modulus and the permanent deformation scalings with suction. Then follow the ε_0 moisture scaling ($\pm 30\%$, ± 1.9 mm), the β exponent (± 0.05 , +1.1 and -2.0 mm) and the subgrade thickness ($\pm 20\%$, ± 1.3 mm), which are of comparable and intermediate magnitude. The weakest sensitivities are the ρ cycle parameter ($\pm 30\%$, +0.6 and -0.5 mm) and the AADTT ($\pm 40\%$, +0.2 and -0.4 mm). Two readings of this ranking are legitimate and one is not.

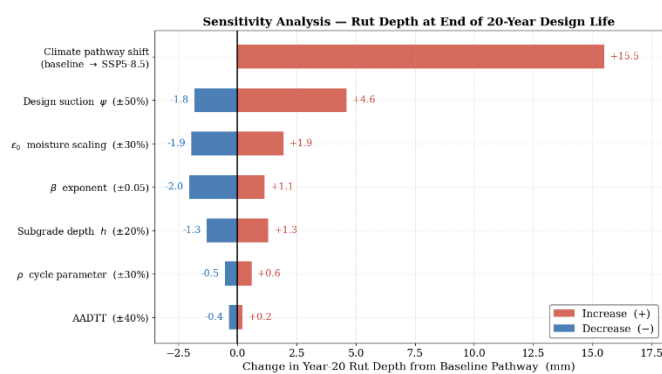


Figure 7. Sensitivity analysis tornado plot.

It is legitimate to conclude that the predicted rut depth is far more sensitive to the assumed design-suction pathway than to traffic growth, so that uncertainty in future traffic volume matters much less than uncertainty in the moisture state, and that measurement effort should be directed at the suction pathway and at the ε_0 and β coefficients. It is also legitimate to note that the deformation-model coefficients together (ε_0 , β , ρ) span a range comparable to the difference between the two climate analogues, so the climate signal is not resolvable beyond that calibration uncertainty. It is not legitimate to

read the size of the climate bar as a measurement of a real climate effect: that bar is as wide as the suction endpoint assumed for it, and it is therefore a statement about the structure and the inputs of the model.

4.8. Comparison with related works

The methodological position of the proposed framework relative to the studies reviewed in Section 2 is summarised in Table 6. The distinguishing feature is the coupling of three modelling levels that are usually treated separately: retention behaviour, suction-dependent stiffness and moisture-scaled permanent deformation, advanced with a single design-suction time series and closed with a sensitivity decomposition. Chu et al. [6] measured permanent deformation of unsaturated subgrade soils under cyclic loading but did not project a suction trajectory. Karumanchi et al. [22] modelled suction and groundwater coupling numerically but without emission-scenario forcing or a design-life rutting criterion. Mendoza-Sanchez et al. [16] carried climate information into the resilient modulus but did not propagate it into a deformation model to produce rut depths. Everton and Erlingsson [7,] [19] provided seasonal permanent-deformation and suction-controlled resilient characterisation, which is the measured basis this framework needs, but over a season rather than a design life. The comparison should be read with one asymmetry kept in view: the four published rows of Table 6 rest on measured or numerically resolved data, whereas the proposed row rests on assumed parameters and prescribed suction pathways. The claim made here is therefore one of scope and traceability, not of superior evidential standing.

Table 6. Comparison of proposed methodology with related works.

Study	Retention (SWCC) coupling	Suction- M_r link	Permanent deformation	Climate (SSP) projection	Sensitivity ranking
Chu et al. [6]	X	X	✓ (measured, cyclic)	X	X
Karumanchi et al. [22]	✓	✓	Partial (FE-based)	X	X
Mendoza-Sanchez et al. [16]	Partial (moisture index)	✓	X	✓	X
Everton & Erlingsson [7,] [19]	✓ (suction-controlled)	✓	✓ (seasonal)	X	X
Proposed framework	✓	✓	✓	Analogue pathways (assumed)	✓ (local, one-at-a-time)

Note: FE, finite element. A tick indicates that the mechanism is represented explicitly, not that it is represented better. The four published rows are supported by measured or numerically resolved data; the proposed framework is not, and its entries in the climate and sensitivity columns refer to assumed SSP-analogue pathways and to a local one-at-a-time screening respectively (Sections 3.4 and 5).

4.9. Limitations and validation status

The framework proposed here is a transparent scenario model, and its limitations follow directly from that status. They are set out in the order of their importance for the interpretation of Section 4, together with what would be required to remove them.

Absence of experimental validation. This is the central limitation. No measured retention curve, resilient modulus or permanent deformation data from the modelled soil are used, so no result in Section 4 has been validated, and the agreement between the two SWCC formulations is a consistency check only.

Removing this limitation requires four steps, in order: measurement of the retention curve of the soil concerned on both drying and wetting branches, by pressure plate and filter paper or chilled-mirror hygrometer, over the 1-10⁵ kPa range; suction-controlled repeated-load triaxial testing at several suction levels and stress states to regress k_1 to k_4 of Equation (6) with reported confidence intervals, following the procedures of [2], [9], [19]; long-duration cyclic loading tests at several suction levels to regress ε_0 , ρ and β of Equations (8) to (10) and to define the soil and stress range over which they hold, following [6], [7], [17]; and field validation at instrumented sections in an arid climate, with suction sensors at subgrade level and periodic transverse profile measurement, so that the computed and observed rut depth histories can be compared. Until at least the first three steps are completed, the framework should be used to compare scenarios, not to size a pavement.

Assumed climate pathways. The design-suction pathways are prescribed, not derived. The framework therefore cannot answer how much suction change a given emission scenario implies; it answers what follows

if a given suction change occurs. The chain required to close this gap, from a downscaled CMIP6 ensemble through a soil-water balance to a suction time series with an ensemble spread, is specified in Section 3.4. Until that chain is implemented, the labels SSP2-4.5 and SSP5-8.5 in this paper denote assumed analogue pathways only.

Neglect of retention hysteresis. A single drying branch is used for a process that involves both drying and wetting. As shown in Section 3.1, these over-estimates the water content of the wetted state and under-estimates its suction, so the computed rut depths are conservative. Quantifying the effect requires paired drying and wetting measurements and a hysteresis model such as that of Pham et al. [32], and the temperature and hysteresis effects reported by Abdollahi and Vahedifard [10] should be included in the same extension.

Structural idealisation. The subgrade is represented as a single 0.6 m layer at a single stress state, with a uniform suction and no depth profile, and neither the asphalt nor the base contributes to the computed rutting. Total pavement rutting is therefore under-estimated while being compared with a threshold that agencies normally apply to the total; the two errors act in opposite directions and neither has been quantified. Extension to a layered structure with depth-varying suction and stress is the natural next step.

Local sensitivity analysis. The screening of Section 4.7 is one-at-a-time about a single reference case. It ranks local influence, it does not apportion variance, and it excludes interactions between parameters, which are expected here because the suction enters both the stiffness and the deformation relationships. A variance-based global analysis over a probabilistic ensemble of pathways would be required for a genuine uncertainty budget.

Adopted performance criterion. The 20 mm line is an adopted analysis threshold, as documented in Section 3.3, and not a specification limit. Conclusions about exceedance are conditional on that choice, and a different agency threshold within the 12-25 mm range in common use would move the crossing point by several years.

Omitted processes and single-soil scope. The analysis is isothermal and ignores the temperature dependence of

the resilient modulus [10], freeze-thaw action, osmotic suction and salinity effects that are common in arid subgrades, and any spatial variability of soil properties. One representative sandy-clay parameter set is used, so the results should not be transferred to other soils without re-derivation.

Finally, Table A1. (in Appendix section) demonstrates Year-by-year cumulative traffic, design suction and computed subgrade rut depth for the three pathways, recomputed from Equations (8)-(13). Every point of Figure 6 can be reproduced from this table.

5. Conclusions

This paper set out a transparent scenario-based framework for arid-region subgrades in which two retention formulations, a suction-dependent resilient modulus model and a moisture-scaled Tseng-Lytton permanent deformation model are advanced year by year over a 20-year design life under prescribed design-suction pathways and an ESAL traffic growth model. The methodological contribution is the two-suction coupling, which separates the annual-average drying trend from the critical post-rainfall wetted state and propagates the latter, rather than an aggregated moisture index, into both the stiffness and the rutting model in one traceable chain. What the computations show, conditional on the assumed parameters, is threefold. First, the mechanism is positional: the design suction range of 55-280 kPa lies on the steep branch of the retention curve, where the computed saturation changes from 54% to 91%, so episodic post-rainfall wetting produces large changes in state while an annual drying trend of similar suction magnitude, acting on the flat branch at 900-1500 kPa, changes saturation by only about seven percentage points. Second, the consequence of that position is a modulus reduction of 19% and 28% at the two analogue endpoints and a year-20 subgrade rut depth of 11.1 mm and 22.0 mm respectively, against 6.5 mm for the constant-climate baseline; only the wettest assumed pathway reaches the 20 mm threshold adopted here, and it does so between years 19 and 20 on a curve that accelerates in the final third of the design life, so a section proportioned on present-day suction would appear adequate for most of its service life. Third, the sensitivity screening ranks the assumed suction pathway

(+15.5 mm) and the design suction (+4.6/-1.8 mm) above the deformation coefficients, with traffic growth (± 0.4 mm) least influential, which locates the decisive uncertainty in the moisture input rather than in the traffic forecast. The corresponding limitation is equally clear and is stated in Section 5: the pathways are prescribed rather than derived from climate model output, the deformation coefficients are assumed, and no measured retention, modulus or rutting data enter the analysis, so all values above are conditional model outputs and the framework is at present a tool for comparing scenarios rather than for sizing a pavement. Its practical value lies in that comparison and in the ranking that follows from it: it shows where the moisture assumption dominates the design outcome, and therefore where measurement effort pays. Work now in preparation follows the priority order of Section 5, namely retention and suction-controlled modulus testing on the soil concerned, regression of the deformation coefficients from long-duration cyclic tests, derivation of the suction pathways from a downscaled CMIP6 ensemble through an explicit soil-water balance, inclusion of retention hysteresis, extension from the subgrade to the full layered structure, and validation against suction and rutting records from instrumented arid highway sections.

Competing Interests Statement

The author declares no conflict of interest.

Data Availability Statement

Data will be made available on request. No measured dataset underlies this study; all inputs are listed in Tables 1-5, and the code implementing Equations (1)-(14), which reproduces every figure and the year-by-year values of Appendix A, is available from the authors on request, so the results can be recomputed from the manuscript alone.

Statement on the Ethical Use of AI Tools

No generative AI tools were used in preparing this manuscript.

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Appendix

Table A1. Year-by-year cumulative traffic, design suction and computed subgrade rut depth for the three pathways, recomputed from Equations (8)-(13). Every point of Figure 6 can be reproduced from this table.

Design year, t	Cumulative ESALs $N(t)$	ψ_{des} SSP2-4.5 (kPa)	ψ_{des} SSP5-8.5 (kPa)	RD baseline (mm)	RD SSP2-4.5 / SSP5-8.5 (mm)
1	0.66×10^6	280.0	280.0	3.45	3.45 / 3.45
2	1.35×10^6	272.6	268.2	4.22	4.34 / 4.41
3	2.05×10^6	265.3	256.3	4.66	4.91 / 5.07
4	2.79×10^6	257.9	244.5	4.97	5.36 / 5.63
5	3.55×10^6	250.5	232.6	5.20	5.74 / 6.13
6	4.33×10^6	243.2	220.8	5.38	6.09 / 6.62
7	5.14×10^6	235.8	208.9	5.53	6.42 / 7.11
8	5.98×10^6	228.4	197.1	5.66	6.74 / 7.62
9	6.85×10^6	221.1	185.3	5.78	7.05 / 8.15
10	7.76×10^6	213.7	173.4	5.88	7.36 / 8.72
11	8.69×10^6	206.3	161.6	5.97	7.67 / 9.33
12	9.65×10^6	198.9	149.7	6.05	7.99 / 10.01
13	10.65×10^6	191.6	137.9	6.12	8.32 / 10.76
14	11.69×10^6	184.2	126.1	6.19	8.66 / 11.62
15	12.76×10^6	176.8	114.2	6.25	9.02 / 12.61
16	13.86×10^6	169.5	102.4	6.31	9.39 / 13.77
17	15.01×10^6	162.1	90.5	6.37	9.78 / 15.16
18	16.20×10^6	154.7	78.7	6.42	10.20 / 16.88
19	17.42×10^6	147.4	66.8	6.47	10.64 / 19.08
20	18.70×10^6	140.0	55.0	6.52	11.12 / 22.01