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Skid Resistance and Surface Texture Deterioration of Urban Asphalt Pavements in Algeria: Assessment and Service Life Estimation

Abdelouahab Bouttout

Bouttout@gmail.com

Cité Nouvelle El-Mokrani

Khalil Dekali

Centre Technique des Travaux Public CTTP. Algiers

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Skid Resistance and Surface Texture Deterioration of Urban Asphalt Pavements in Algeria: Assessment and Service Life Estimation

Highlights

- Continuous friction (61.1 lane-km) and 125 sand-patch tests describe three Algiers road sites.
- Two thirds of the surveyed length lies below the friction level used for dual carriageways in UK practice.
- Mean texture depth (median 0.23 mm) is far below 0.6 mm, so wet friction falls sharply with speed.
- An equilibrium polishing model gives the aggregate PSV needed for each Algerian traffic class.
- Above 1500 heavy vehicles/day/direction, skid resistance limits wearing-course life to <8–10 years unless PSV ≥ 60.
- A traffic-based service-life model separates light- and heavy-vehicle effects and is applied to 11 Algiers count stations.

Abstract

The Algerian pavement design Technical document prescribes a new wearing course after about 8–10 years, when undefined *condition indicators* decline. This study proposes friction-based indicators and a traffic-based model of the functional service life of asphalt wearing courses. Continuous longitudinal friction (61.1 lane-km) and 125 sand-patch tests were analysed on an urban expressway, an arterial and four interchange loops near Algiers and compared with investigatory levels from UK practice. Of the surveyed length, 66.7 % had friction below 0.39 and 84.0 % below 0.45. The median texture depth was 0.23 mm, so wet friction falls sharply with speed, and friction was uncorrelated with texture. A literature equilibrium polishing law was combined with an asymptotic time-decay law, Technical document traffic classes, lane factors, traffic growth, a light-vehicle polishing weight, a speed-dependent texture gate and the Technical document's structural life. The model was run by Monte Carlo simulation. For 1500–3000 heavy vehicles/day/direction, PSV ≥ 60 is needed for an even chance of 8 years above the 0.40 level. Applied to 2018 counts at 11 Algiers stations (2,600–21,500 vehicles/day/direction, 1.5–13 % heavy vehicles), the model predicts skid-governed lives below 20 years only on the two busiest roads. Its ranking agreed with an independent network model ($r = 0.95$). A simulated calibration study shows that 20 sections surveyed annually for five years would predict life within about 1.5 years. Skid resistance, not structural capacity, should trigger renewal on heavily trafficked roads, and minimum PSV and texture requirements should be added to the Technical document.

Keywords: skid resistance; macrotexture; wearing course; pavement deterioration model; traffic loading; heavy vehicles; service life; Algeria

1. Introduction

The Algerian *Catalogue de Dimensionnement des Chaussées Neuves* [1–3] governs the structural design of new pavements on the main road network (RP1 and RP2, about 18,400 km). It fixes design lives of 15–25 years, calculation risks and traffic classes (TPL3–TPL7, expressed in heavy vehicles (PL) per day and per direction). It also prescribes a bituminous-concrete wearing course of 6–8 cm on RP1. The Technical document is explicit about the maintenance that its design lives presuppose: *"a preventive maintenance (laying of a new wearing course) shall be carried out as soon as certain condition indicators show a decrease of the level of service, and before structural distress appears (in general after 8 to 10 years)"* [1]. It does not, however, say which indicators should be used, what thresholds apply or how fast they are expected to deteriorate. For a road user, the most safety-critical surface property is wet skid resistance. Friction is therefore a natural candidate for at least one of these indicators.

Skid resistance depends on two scales of texture. Microtexture (wavelengths below 0.5 mm) governs friction at low speed. Macrotexture (0.5–50 mm) drains the contact area and controls how quickly friction falls as speed increases [4–6]. The International Friction Index (IFI) formalises this split: a speed constant S_p, obtained from a macrotexture measurement, scales friction measured at one slip speed to a reference slip speed of 60 km/h [7, 8]. Under traffic, microtexture is polished. Field skid resistance typically decreases from an initial value towards an equilibrium that depends on the volume of commercial vehicles and on the polishing resistance of the aggregate, expressed by the Polished Stone Value (PSV) [9–11]. Several prediction models of this kind have been developed from network data. They include the equilibrium model of Szatkowski and Hosking [9], network-wide regression models for motorways and single carriageways [12, 13], survival models of friction degradation [14] and laboratory-based polishing models [15]. Long-term monitoring has shown that macrotexture and skid resistance can evolve in opposite directions under traffic, so a model based on texture alone cannot predict friction [16, 17].

These models are rarely applied in North Africa, where friction surveys are not routine and the design Technical document contains no requirement on aggregate polishing resistance or surface texture [3, 18]. This paper uses continuous friction and texture data collected on three road sites in the Algiers region, together with traffic counts on eleven roads, to answer four questions:

- What is the present skid-resistance and macrotexture condition of the asphalt wearing courses, and how much length would need treatment under internationally used investigatory levels?
- Is the measured state consistent with the polishing behaviour predicted by literature models, and what does the very low macrotexture imply for friction at traffic speed?
- For each traffic class of the Algerian Technical document, how long can a renewed wearing course keep its skid resistance above investigatory levels? Is the Technical document's 8–10-year renewal interval achievable, and what aggregate and texture requirements would make it so?

- Can these relations be expressed as a general model of the functional service life of a wearing course as a function of traffic volume, heavy-vehicle share and cumulative loading, and how could such a model be calibrated and validated on Algerian roads?

The contribution is methodological and practical. The study links a one-off network survey to literature deterioration models in the absence of local calibration data. It converts the result into condition indicators, thresholds and material requirements that could complement the Technical document. Fig. 1 summarises the framework.

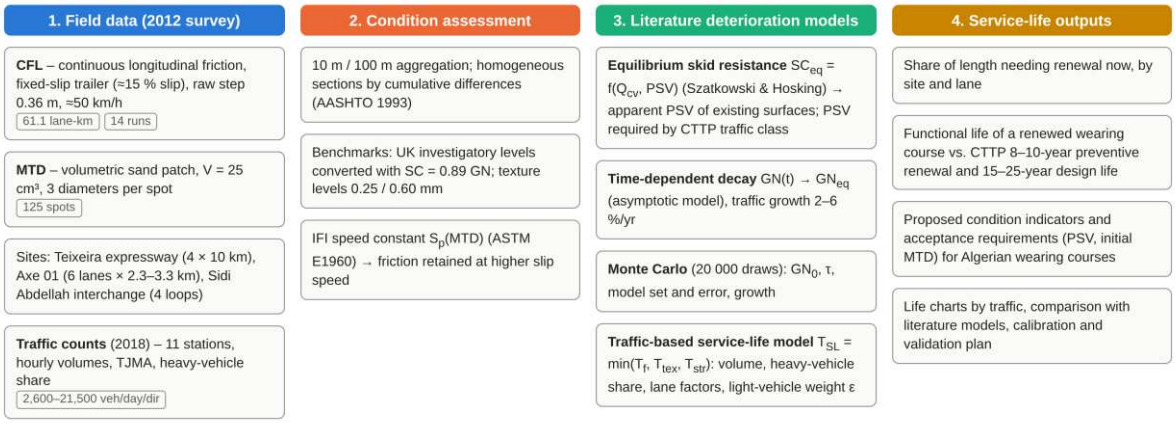


Fig. 1. Analysis framework: field data, condition assessment, literature deterioration models and service-life outputs.

2. Materials and methods

2.1. Sites and survey

The data comprise one survey of three sites (Table 1). The measurements were carried out in May 2012 (the texture records of the first site are dated 27 May 2012). The first site, labelled *Teixeira* in the survey, is a dual two-lane urban expressway in the south-western Algiers area. It was surveyed between PK 7+000 and PK 17+000, and the field notes identify structures at Souidania and Douera. The second, *Axe 01*, is a dual three-lane urban arterial in the new town of Sidi Abdellah (about 2.3–3.3 km per lane). The third comprises the four loops of the Sidi Abdellah interchange (0.9–1.3 km each). All wearing courses are bituminous. Their age, mix type, aggregate source and traffic were not available, and these unknowns are handled by scenarios (Section 2.6).

Table 1. Survey sites and data.

Site	Type	Friction runs (lane-km)	Sand-patch tests	Notes
Teixeira	Urban expressway, 2 × 2 lanes	4 runs (40.0)	79 (4 lines, every 500 m)	Lane 1 and lane 2, both directions
Axe 01	Urban arterial, 2 × 3 lanes	6 runs (16.7)	36 (6 lanes, every 500 m)	Sidi Abdellah new town
Sidi Abdellah interchange	Four loops (ramps)	4 runs (4.4)	10	Speed and water flow recorded
Total		14 runs (61.1)	125	

2.2. Friction measurement

Friction was recorded as the longitudinal friction coefficient CFL every 0.36 m. For the interchange loops, the raw files contain the traction (drag) force, the vertical load, the vehicle speed and the water flow rate, and CFL equals traction divided by load. These outputs, and the CFL label used in French practice for this device family, correspond to a fixed-slip continuous friction tester of the GripTester family, here integrated into the survey vehicle (Fig. 2a, b). Such a device works at a relative slip of about 15 %, i.e. a slip speed of roughly 8 km/h at 50 km/h [19]. The test speed on the expressway and the arterial, the water-film depth and the calibration records were not documented in the data files. Mean survey speed on the loops was 56–61 km/h (10th–90th percentile 36–70 km/h). Raw data were averaged over 10 m, the averaging length used for GripTester contractual checks [19], and over 100 m for display. CFL is treated as equivalent to the GripTester Grip Number (GN). SCRIM-type sideway-force coefficients were obtained with the relation published by TRL and reproduced by Isasa et al. [13]:

$$\mathrm{SC} = 0.89\,\mathrm{GN} \tag{1}$$

Eq. (1) has a reported correlation of 0.97 [13]. It is used only to place the Algerian data on the scale of published investigatory levels and polishing models, not as a substitute for a local device correlation.

The friction survey equipment is shown in Fig. 2a, b. The measuring system is installed on a light pick-up survey vehicle fitted with roof-mounted warning beacons (Fig. 2a), so that measurements can be made at a steady speed within live traffic, without a towed unit. The measuring wheel and its test tyre are mounted under the vehicle chassis (Fig. 2b). During a run, a controlled water flow wets the pavement in front of the wheel, the wheel is braked at a fixed slip ratio, and the drag and vertical forces are recorded continuously; their ratio gives the CFL. Two consequences follow from this configuration. First, because the slip speed is low (about 8 km/h), the CFL mainly reflects the microtexture of the surface, and the contribution of macrotexture, which governs friction at traffic speed, had to be assessed separately with the sand-patch tests (Section 2.3) and the IFI relations (Section 2.6). Second, continuous recording at a fine spacing provides the spatial resolution needed to delineate homogeneous sections (Section 2.4), which spot tests could not provide.

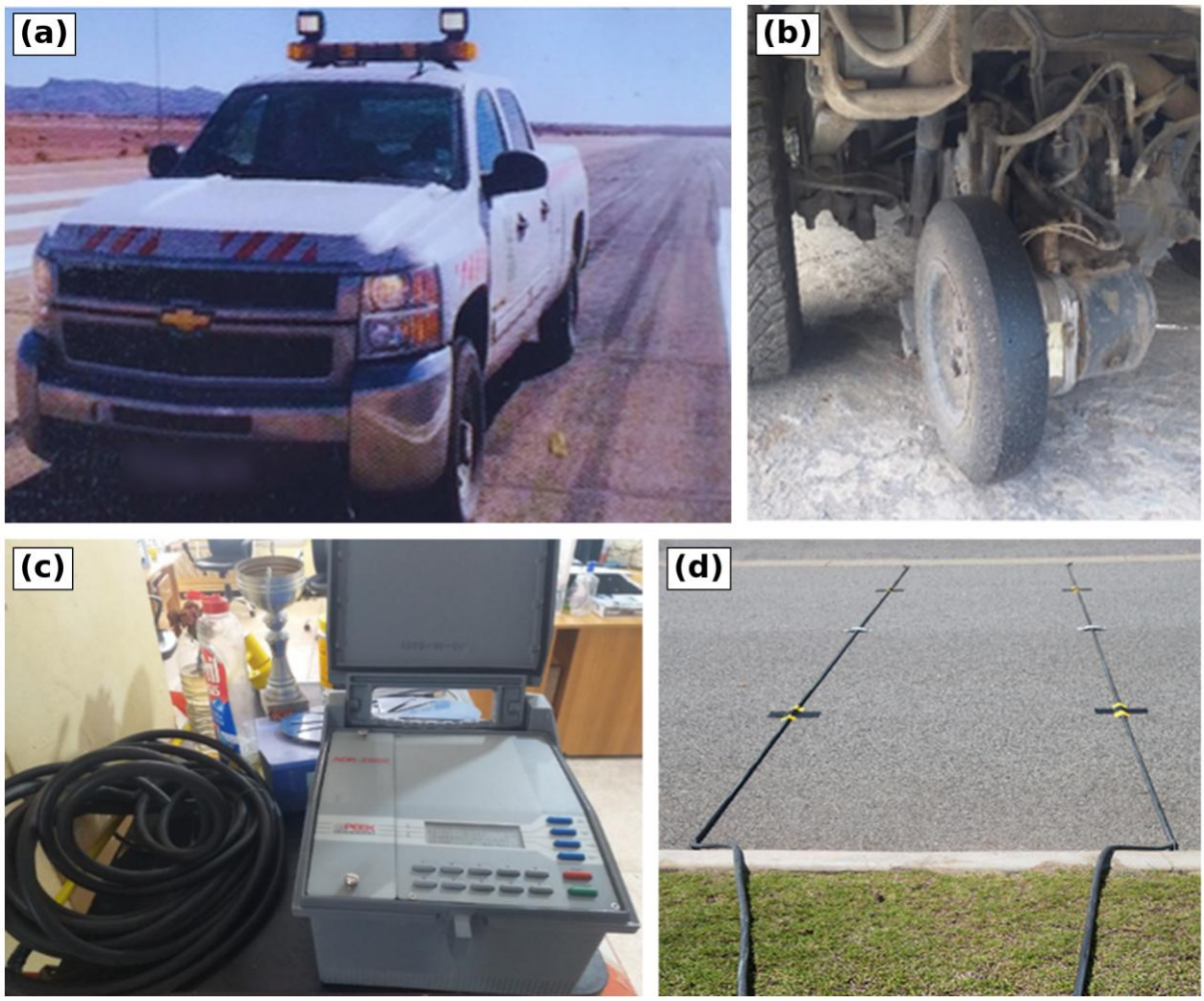


Fig. 2. Equipment used for the field measurements: (a) survey vehicle of the continuous friction measuring device; (b) friction measuring wheel mounted under the vehicle; (c) portable automatic traffic counter (Peek ADR-2000) with its pneumatic road tubes; (d) typical installation of two pneumatic tubes across the carriageway.

2.3. Macrotexture measurement

Mean texture depth (MTD) was measured with the volumetric (sand-patch) method [20, 21]. A volume V = 25,000 mm³ of material was spread into a circle, three diameters were read, and

$$\mathrm{MTD} = \frac{4V}{\pi D^2} \tag{2}$$

where D is the mean diameter (mm). All 125 records are consistent with Eq. (2) and V = 25 cm³. The coefficient of variation of the three diameters was 1.1 % (median). One reading (Teixeira, return, line P1, PK 10+000: 70.2 cm against 40.5 and 39.8 cm) is probably a transcription error. It was retained, and it lowers the MTD of that spot from about 0.20 to 0.13 mm.

2.4. Data processing and homogeneous sections

For each run, homogeneous sections were delineated on the 10 m CFL series with the cumulative difference approach of AASHTO [22]. The cumulative difference variable is

$$Z_k = \sum_{i=1}^{k} (c_i - \bar{c})\,\Delta x, \qquad k = 1, \ldots, n \tag{3}$$

where c_i is the 10 m value, $\bar{c}$ the run mean and Δx = 10 m. The series was split recursively at the maximum of $|Z_k|$. A split was kept when both parts were at least 200 m long, their means differed by at least 0.03 and

Welch's *t*-test gave $p < 0.01$. This produced 62 sections with median lengths of 0.42–0.59 km. To relate friction and texture locally, each sand-patch spot was paired with the mean CFL within ±50 m. This assumes that the survey origin coincides with the first chainage of each line (PK 7+000 outbound and PK 17+000 return for Teixeira; PK 0+910 outbound and PK 3+100 return for Axe 01), which gave 114 pairs. The loop texture spots could not be located on the friction runs and were analysed separately.

2.5. Condition benchmarks

Algeria has no official investigatory levels for skid resistance. The UK site-category levels [23] were therefore used as external benchmarks (Table 2) and converted to GN with Eq. (1). Being below an investigatory level is a trigger for site investigation, not proof of an unsafe road [23]. For macrotexture, two published values bracket the analysis. A sand-patch depth above 0.60 mm is considered adequate for most roads [24], and surfaces below 0.25 mm have been classified as overly smooth [25]. TRL work found that accident risk on high-speed roads increased below a sensor-measured texture depth of about 0.7 mm [26].

Table 2. Benchmarks used in the assessment (external references; no Algerian threshold exists).

Indicator	Level	Equivalent GN/CFL (Eq. 1)	Applied to	Source
Investigatory level, dual carriageway non-event (cat. B)	SC 0.35	0.39	Teixeira, Axe 01	[23]
Investigatory level, single carriageway/urban (cat. C)	SC 0.40	0.45	Teixeira, Axe 01 (sensitivity)	[23]
Investigatory level, bends and junction approaches (S1, Q)	SC 0.45–0.50	0.51–0.56	Interchange loops	[23]
Contractual minimum, new surface, site class 1 (10 m mean)	GN 0.39	0.39	Renewed surfaces	[19]
Texture depth, adequate	MTD > 0.60 mm	–	All	[24]
Texture depth, overly smooth	MTD < 0.25 mm	–	All	[25]

2.6. Texture and the speed dependence of friction

Following ASTM E1960 [8], the IFI speed constant (km/h) is obtained from the sand-patch depth as

$$S_p = -11.6 + 113.6\,\mathrm{MTD} \tag{4}$$

As a check, S_p was also computed through the mean profile depth, with MPD = (MTD − 0.2)/0.8 from ASTM E1845 [27] and $S_p = 14.2 + 89.7 \cdot \mathrm{MPD}$ [8]. Friction at another slip speed then follows the PIARC exponential model [7, 28]:

$$\mathrm{FR}(S) = \mathrm{FR}(S_0)\exp\left(\frac{S_0 - S}{S_p}\right) \tag{5}$$

with $S_0 \approx 8$ km/h for the fixed-slip device [19] and $S = 60$ km/h, the IFI reference slip speed. Because device-specific IFI harmonisation constants (A, B) were not available for the device used, the analysis reports the ratio $FR(60)/FR(8)$. This ratio isolates the effect of macrotexture and does not depend on the device. On the loops, where speed varied, the within-run regression of ln(CFL) on speed gives an apparent speed constant $S_{p,\mathrm{app}} = -0.15/\mathrm{slope}$, since the slip speed is about 0.15 V. This was compared with Eq. (4).

2.7. Deterioration models

2.7.1. Equilibrium skid resistance

Polishing by commercial traffic drives skid resistance towards an equilibrium value. Szatkowski and Hosking [9] related this equilibrium to commercial vehicles per lane per day (Q) and to PSV:

$$\mathrm{SC_{eq}} = a - b\,Q + c\,\mathrm{PSV} \tag{6}$$

Two coefficient sets are quoted in the secondary literature. Set 1 is $a = 0.024$, $b = 0.663 \times 10^{-4}$, $c = 0.010$ (as tabulated in [13]). Set 2 is $a = 0.033$, $b = 0.664 \times 10^{-4}$, $c = 0.0098$. Both were used, and the traffic term was taken as negative, as the physics requires. Eq. (6) was derived for less than about 4000 commercial vehicles per day, and later TRL work found a weaker traffic effect at higher volumes. Results for the heaviest class (TPL7) are therefore extrapolations and are likely to be conservative. Following the Technical document, 90 % of heavy vehicles are assumed to use the slow lane of a two-lane carriageway [1]:

$$Q = \lambda\,\mathrm{PL}, \qquad \lambda = 0.9 \tag{7}$$

Eq. (6) was used in two ways. Inverted, it gives the *apparent PSV* that would explain the measured friction for a given traffic. It also gives the PSV required to keep the equilibrium at an investigatory level $\mathrm{SC_{IL}}$:

$$\mathrm{PSV_{req}} = \frac{\mathrm{SC_{IL}} - a + b\,Q}{c} \tag{8}$$

2.7.2. Time-dependent functional life

Field skid resistance typically declines asymptotically from an initial value to an equilibrium, with seasonal oscillations around it [10, 11, 17]. This behaviour was represented by

$$\mathrm{GN}(t) = \mathrm{GN_{eq}}(t) + \left[\mathrm{GN_0} - \mathrm{GN_{eq}}(t)\right] e^{-t/\tau} \tag{9}$$

where $GN_{eq}(t)$ is given by Eqs. (1) and (6) with $Q(t) = Q_0(1 + g)^t$, and τ is a time constant. The *functional life* T_f of a renewed wearing course is the first time at which the predicted GN falls below the investigatory level:

$$T_f = \min\left\{t:\ \mathrm{GN}(t) < \frac{\mathrm{SC_{IL}}}{0.89}\right\} \tag{10}$$

Uncertainty was propagated by Monte Carlo simulation, with 20,000 draws for each combination of traffic class (TPL4–TPL7), PSV (45–65) and investigatory level (Table 3). The horizon was truncated at 25 years.

Table 3. Inputs of the functional-life simulation and their status.

Input	Distribution / value	Status and basis
Heavy vehicles per day and direction at opening	Uniform within the TPL class bounds (TPL7: 3000–6000)	Official classes [1]
Share of heavy vehicles in the slow lane, λ	0.9	Technical document default [1]
Traffic growth, g	Uniform 2–6 %/yr	Assumption around the Technical document example rate of 4 % [1]
Initial GN after early-life trafficking, GN_0	Uniform 0.5–0.9	Range of 6-month GN values reported for new surfaces [19]
Time constant, τ	Uniform 1–3 years	Assumption; equilibrium reached within roughly 3–9 years [17]
Equilibrium coefficients	Set 1 or Set 2 (50/50)	Literature [9, 13]
Model error on SC_{eq}	Normal, mean 0, s.d. 0.03	Assumption (structural uncertainty)
PSV of the surfacing aggregate	45, 50, 55, 60, 65	Design variable (scenario)

Input	Distribution / value	Status and basis
Investigatory level	SC 0.35, 0.40, 0.45	External benchmark [23]

Every quantity in the paper is one of four kinds: measured (CFL, MTD), official (Technical document classes and defaults), literature (models, conversion factors, benchmarks) or assumed (Table 3). Results that depend on assumed values are reported as ranges or probabilities.

2.8. Traffic data

Automatic seven-day counts made in 2018 at 13 stations on wilaya roads of Algiers (CW45 to CW245) were used. Two stations (P-60, P-62) contain no automatic data, so 11 stations were used. The counts were made with portable automatic counters of the type shown in Fig. 2c, connected to two pneumatic tubes laid across the carriageway and fixed to the surface (Fig. 2d). Each axle crossing a tube sends an air pulse to the counter; with two tubes a short, known distance apart, the direction of travel is identified and each direction is counted separately. The count files used here, however, contained aggregated volumes only, without axle-based classification or spot speeds, so the heavy-vehicle share had to be obtained from manual classification. For each station and direction the files give hourly volumes, the average daily traffic (TJM), its annual equivalent (TJMA, obtained with seasonal correction factors), peak, daytime and night traffic. The heavy-vehicle (PL) share was estimated from manual classification during 6–8 daytime hours. At most stations the manual counters recorded mainly the heavy classes (P3–P6), and the share of vehicles classified manually was only 2–18 % of the automatic count. The PL share was therefore estimated as the number of heavy vehicles classified manually divided by the automatic count for the same periods, which assumes that heavy vehicles were counted exhaustively. Where light vehicles were also classified (P-81, direction 2; P-89, 65–73 % coverage), this estimate is 1–3 percentage points lower than the classified share. The estimates are therefore treated as approximate and scenario ranges are used. The counts are taken as representative of the range of urban and peri-urban roads of the Algiers region (Section 3.7).

2.9. Traffic-based functional service-life model

The relations of Section 2.7 were generalised into a model of the functional service life of a bituminous wearing course as a function of traffic. The choice of model form follows three considerations. First, wet skid resistance is the surface property for which deterioration under traffic is best documented and for which the Technical document's renewal rule is most relevant [9, 11, 14]. Second, Algerian data consist of one condition survey and short traffic counts, which rules out purely statistical models (regression, survival or Markov models) that need repeated observations [12–14]. Third, the model must separate the effects of light and heavy vehicles, which act on the surface through different mechanisms and in different proportions. A mechanistic-empirical structure with physically interpretable parameters was therefore adopted. It can be run with literature values today and recalibrated when monitoring data accumulate.

Traffic module. For a carriageway carrying T vehicles/day/direction (TJMA) with heavy-vehicle share p, the daily heavy and light vehicles in the most-loaded lane are

$$Q_{\mathrm{HV}}(t) = \lambda_H \, p \, T \, (1+g)^t \tag{11}$$

$$Q_{\mathrm{LV}}(t) = \lambda_L\,(1-p)\,T\,(1+g)^t \tag{12}$$

where λ_H is the catalogue lane factor for heavy vehicles (0.9 on two-lane carriageways, 0.8 on three-lane carriageways [1]) and λ_L the share of light vehicles in the same lane (0.5 assumed). Cumulative quantities after t years follow by integration. The cumulative heavy vehicles per lane are

$$N_{\mathrm{HV}}(t) = 365\,Q_{\mathrm{HV}}(0)\,\frac{(1+g)^t-1}{\ln(1+g)} \tag{13}$$

the cumulative number of equivalent light vehicles used by HDM-4 for surface wear, counting one heavy vehicle as ten light vehicles, is [29]

$$\mathrm{NELV}(t) = N_{\mathrm{LV}}(t) + 10\,N_{\mathrm{HV}}(t) \tag{14}$$

and the cumulative number of equivalent 13-t axles per direction, as defined by the Technical document with the aggressiveness coefficient A (0.6 for bituminous structures on RP1), is [2]

$$\mathrm{TCE}(t) = 365\,p\,T\,A\,\frac{(1+g)^t-1}{g} \tag{15}$$

Skid-resistance module. Polishing is driven by an equivalent polishing traffic in which light vehicles are weighted by a factor ε relative to heavy vehicles:

$$Q_p(t) = Q_{\mathrm{HV}}(t) + \varepsilon\,Q_{\mathrm{LV}}(t) \tag{16}$$

Eq. (6) is generalised to $SC_{\mathrm{eq}}(t) = a - b\cdot Q_{\mathrm{p}}(t) + c\cdot\mathrm{PSV} + \delta_{\mathrm{env}}$. With $\varepsilon = 0$ and $\delta_{\mathrm{env}} = 0$ this reduces to the original Szatkowski–Hosking relation, which was fitted to commercial-vehicle flows only. $\varepsilon > 0$ represents an additional polishing contribution of light vehicles, which matters on urban roads that carry very large light-vehicle volumes. Its upper bound of 0.1 corresponds to the 1:10 equivalence used by HDM-4 for surface wear [29]; $\varepsilon = 0.05$ is used as a sensitivity case. δ_{env} collects seasonal, temperature and climatic effects on measured friction. It is not identifiable from a single survey and is represented by the model error of Table 3. The skid-resistance life T_{f} then follows from Eqs. (9) and (10).

Texture, speed and structural modules. No texture-deterioration law could be calibrated for dense asphalt. Long-term monitoring shows that macrotexture changes little, or even increases, under traffic while friction decreases [17]. Texture therefore enters the model as a gate that depends on the operating speed V: $T_{\mathrm{tex}} = 0$ if the initial texture MTD_0 is below $\mathrm{MTD}_{\mathrm{min}}(V)$, and $T_{\mathrm{tex}} = \infty$ otherwise. Provisionally, $\mathrm{MTD}_{\mathrm{min}} = 0.60$ mm for $V \geq 80$ km/h and 0.40 mm below (Table 11). The structural reference life T_{str} is the time at which the cumulative axle loads of Eq. (15) reach the design value of the Technical document structure for the traffic class, i.e. the class upper bound over 20 years at 4 %/yr [1, 2]. The functional service life of the wearing course is the shortest of the three:

$$T_{\mathrm{SL}} = \min\left(T_f,\ T_{\mathrm{tex}},\ T_{\mathrm{str}}\right) \tag{17}$$

For a section in service, the model is updated with the measured condition by replacing GN_0 in Eq. (9) with the measured GN and counting t from the survey date. Uncertainty is propagated with the Monte Carlo scheme of Section 2.7.2 (8000 draws per station).

2.10. Model comparison, consistency checks and calibration strategy

The model was compared with deterioration and service-life models reported in the literature (Table 9). For a quantitative comparison, the network model of Isasa et al. [13], fitted to 66 single-carriageway segments, was applied to the 11 stations:

$$\mathrm{MSSC} = 83.661 - 8.138\log_{10}\mathrm{AADT} - 0.004\,\mathrm{AADT_{HV}} \tag{18}$$

where MSSC is the mean summer SCRIM coefficient (×100), AADT the two-way traffic and $\mathrm{AADT_{HV}}$ the two-way heavy-vehicle traffic. The logarithm base is not stated in the source and was taken as 10. Agreement between the two models was measured with Pearson's *r*, Spearman's ρ and the mean difference.

No time series of friction is available for the counted roads, so the model could not be validated against observed deterioration. Two checks were made instead. The first is a lane-contrast test on the Teixeira expressway. Lanes of the same carriageway share age, mix and climate, so with $\varepsilon = 0$ the model predicts an equilibrium difference $\Delta SC = b \cdot Q_{\mathrm{HV,dir}} \cdot (\lambda_1 - \lambda_2)$ between the slow and fast lanes. The measured contrast can be inverted for the heavy-vehicle traffic it implies, and this value compared with the counted roads. The second check is a simulation-based calibration design. Synthetic friction surveys were generated with the model for n = 10, 20 or 40 sections with traffic drawn from the counted range (2,500–25,000 vehicles/day/direction, 2–25 % heavy vehicles), known parameters (PSV 55, $\varepsilon = 0.02$, $\tau = 2$ years), a random section effect (s.d. 0.03) and survey noise (s.d. 0.03). The global parameters ($a + c \cdot \mathrm{PSV}$, b, ε, τ, GN_0) were re-estimated by non-linear least squares from k = 2, 3 or 5 annual surveys and used to predict 20 hold-out sections for 8 further years. Predictive performance was summarised by

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_j \left(\hat{y}_j - y_j\right)^2}, \qquad R^2 = 1 - \frac{\sum_j \left(\hat{y}_j - y_j\right)^2}{\sum_j \left(y_j - \bar{y}\right)^2} \tag{19}$$

together with the mean absolute error (MAE), the mean bias, the coverage of nominal 90 % prediction intervals and the median absolute error of the predicted service life. Each design was replicated 60 times.

3. Results

3.1. Skid resistance condition

Table 4. Friction statistics of the 10 m CFL values and share of length below the GN benchmarks.

Site	Run	Length (km)	Mean	S.d.	P10	P90	% < 0.39	% < 0.45	% < 0.51
Teixeira	Outbound, lane 1	10.00	0.332	0.062	0.252	0.406	85	96	100
Teixeira	Outbound, lane 2	10.00	0.418	0.085	0.294	0.522	37	57	83
Teixeira	Return, lane 1	10.00	0.373	0.048	0.311	0.431	66	95	100
Teixeira	Return, lane 2	10.00	0.443	0.057	0.380	0.521	18	58	85
Axe 01	Outbound, lane 1	3.10	0.189	0.025	0.163	0.220	100	100	100
Axe 01	Return, lane 1	2.49	0.170	0.015	0.151	0.187	100	100	100
Axe 01	Outbound, lane 2	3.09	0.164	0.022	0.138	0.189	100	100	100
Axe 01	Return, lane 2	2.40	0.238	0.025	0.199	0.263	100	100	100
Axe 01	Outbound, lane 3	3.29	0.280	0.072	0.178	0.360	94	99	100
Axe 01	Return, lane 3	2.33	0.319	0.058	0.257	0.401	88	99	100
Sidi Abdellah	Loop 1	1.34	0.271	0.038	0.210	0.316	100	100	100
Sidi Abdellah	Loop 2	1.24	0.230	0.034	0.182	0.272	100	100	100

Site	Run	Length (km)	Mean	S.d.	P10	P90	% < 0.39	% < 0.45	% < 0.51
Sidi Abdellah	Loop 3	0.90	0.429	0.093	0.332	0.568	47	68	72
Sidi Abdellah	Loop 4	0.96	0.198	0.046	0.160	0.228	100	100	100

GN 0.39, 0.45 and 0.51 correspond to SCRIM investigatory levels of 0.35, 0.40 and 0.45 through Eq. (1).

Table 4 and Figs. 3–4 summarise the friction data. On the Teixeira expressway, lane 1 (mean 0.33 outbound, 0.37 return) is consistently less skid-resistant than lane 2 (0.42 and 0.44). This is consistent with heavier polishing in the slow lane. Below GN 0.39 lie 85 % (outbound) and 66 % (return) of lane 1, compared with 37 % and 18 % of lane 2. Friction increases along the outbound direction from about 0.26 to 0.50 (Fig. 3), which suggests surfacing sections of different age or composition. The Axe 01 arterial is in much poorer condition. Its lanes 1 and 2 have means of 0.16–0.24 with low dispersion (coefficient of variation 0.09–0.13), lane 3 has means of 0.28–0.32, and 97 % of the arterial length is below GN 0.39. On the interchange, three loops have means of 0.20–0.27, about half of the 0.51–0.56 recommended for bends. Only loop 3 (mean 0.43) partly meets the benchmark. Weighted by length, 66.7 % of the 61.1 lane-km surveyed is below GN 0.39 and 84.0 % below 0.45. The segmentation identified 62 homogeneous sections, of which 44 (37.4 km, 61 % of the length) have a mean below 0.39 (Fig. 3).

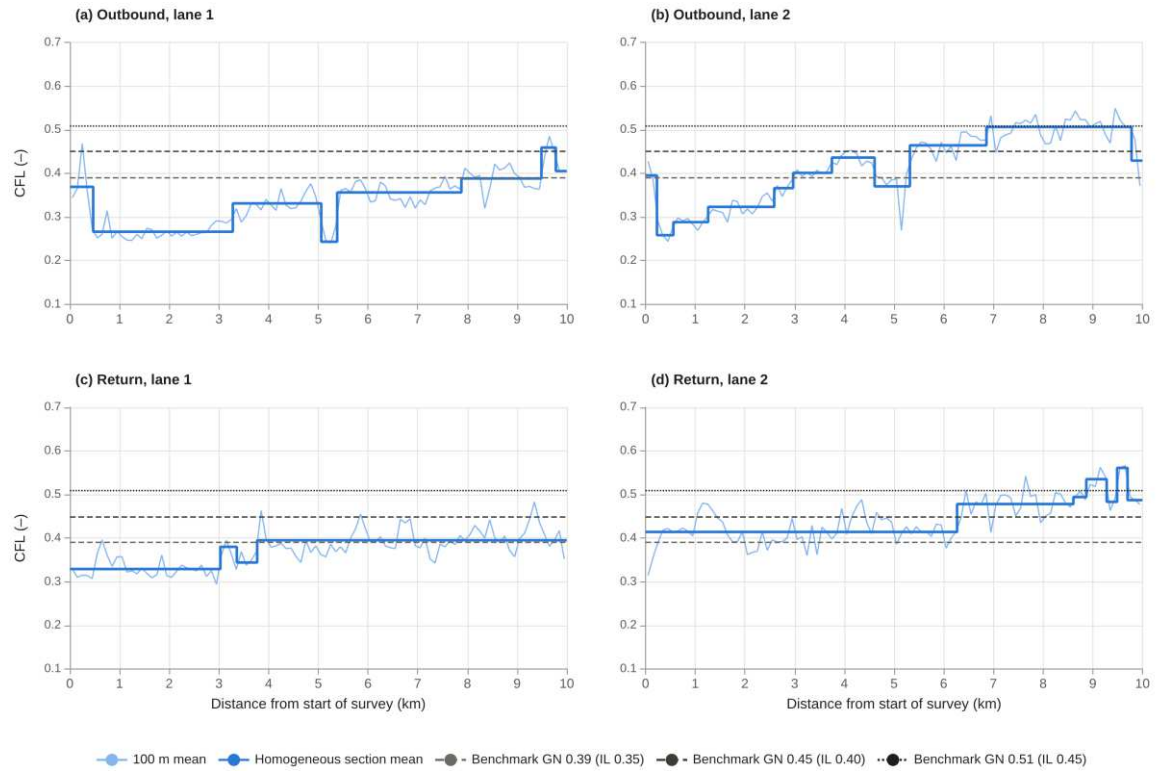


Fig. 3. Longitudinal CFL profiles on the Teixeira expressway: 100 m means and homogeneous sections from the cumulative difference approach. Dashed and dotted lines are the benchmark levels of Table 2.

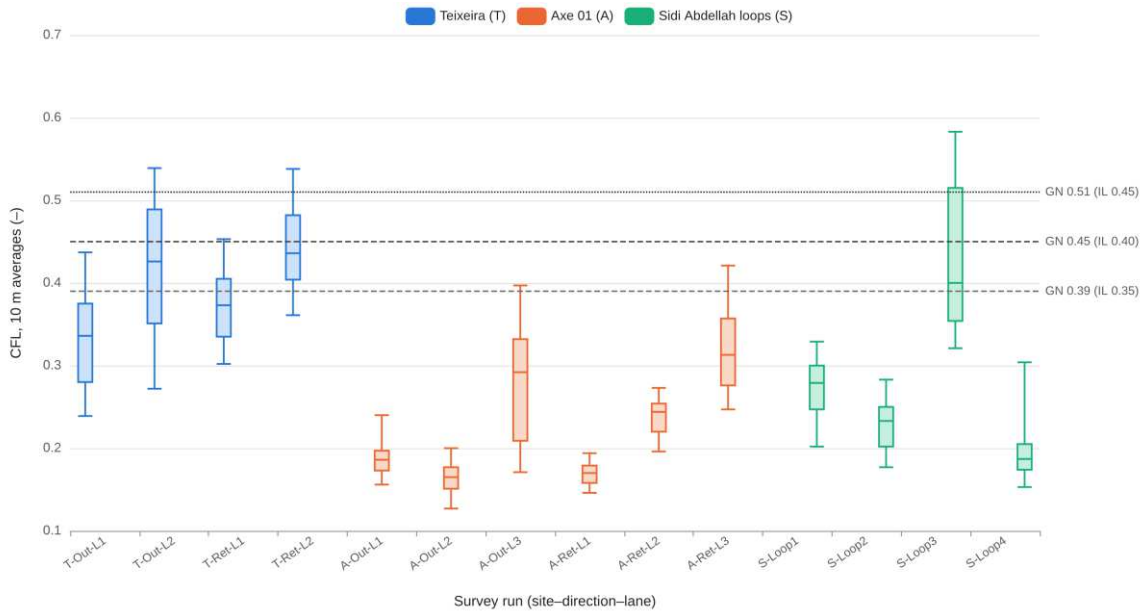


Fig. 4. Distribution of 10 m CFL values for the 14 runs (box: quartiles and median; whiskers: 5th–95th percentiles). T: Teixeira; A: Axe 01; S: Sidi Abdellah loops; Out/Ret: direction; L: lane.

3.2. Macrotexture

The texture depths are uniformly low (Fig. 5a). Over the 125 tests the mean MTD is 0.243 mm (median 0.227 mm, range 0.092–0.576 mm). 60.8 % of the tests are below the 0.25 mm *overly smooth* level, 95.2 % are below 0.40 mm, and none reaches 0.60 mm. The site medians are 0.22 mm (Teixeira), 0.25 mm (Axe 01) and 0.25 mm (loops). On Teixeira, line P1 outbound has a higher median (0.28 mm) than the three other lines (0.19–0.21 mm). Texture depths this low are typical of dense, fine-graded or binder-rich surfaces, or of surfaces whose aggregate has been embedded or covered by binder (flushing). The data available here cannot distinguish between these causes.

Locally, CFL and MTD are not correlated (Fig. 5b; Spearman $\rho = -0.18$, $p = 0.057$, $n = 114$; Teixeira $\rho = -0.13$, $p = 0.25$; Axe 01 $\rho = 0.10$, $p = 0.56$). This is expected. At a slip speed of about 8 km/h, the device measures mainly the microtexture contribution, whereas macrotexture controls the decrease of friction with speed [4, 17]. The two indicators are therefore complementary, not redundant.

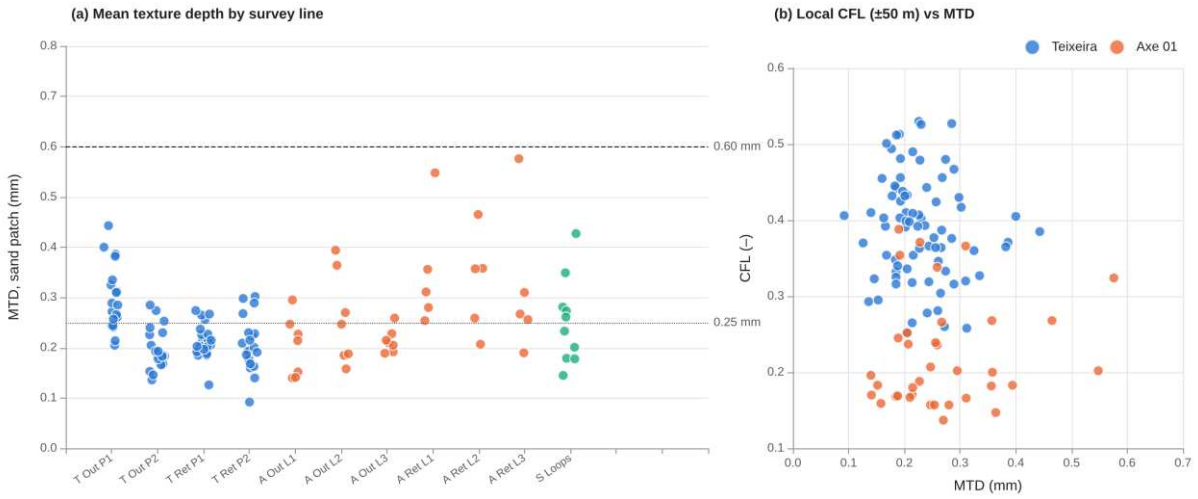


Fig. 5. (a) Mean texture depth by survey line, with the 0.60 mm adequacy level [24] and the 0.25 mm overly-smooth level [25] (blue: Teixeira; orange: Axe 01; green: Sidi Abdellah loops). (b) Local CFL (mean within ±50 m) against MTD.

3.3. Speed dependence of friction

The median speed constants of the survey lines are 9–29 km/h with Eq. (4) and 14–32 km/h through the MPD route (Fig. 6a). For MTD = 0.25 mm, Eq. (5) gives $FR(60)/FR(8)$ = 0.05–0.07, i.e. more than 90 % of the low-speed friction is lost at 60 km/h slip speed. For 0.6 mm the ratio is about 0.40, and for 1.0 mm about 0.60 (Fig. 6b). These values extrapolate the IFI relations towards the low end of the range covered by the PIARC experiment [7], so the absolute numbers are indicative. The trend agrees with TRL findings, however: the effect of texture on friction loss is greatest below about 0.7 mm [26]. The loop data provide independent support. On loops 2 and 4, ln(CFL) decreased significantly with survey speed (slopes −0.0062 and −0.0150 per km/h, $p < 0.001$), giving apparent speed constants of 24 and 10 km/h. These are of the same order as the speed constants predicted from the loop texture depths with Eq. (4) (median 16 km/h, range 5–37 km/h). On loops 1 and 3 the slope was not significant ($p > 0.3$), probably because speed and geometry vary together along a loop.

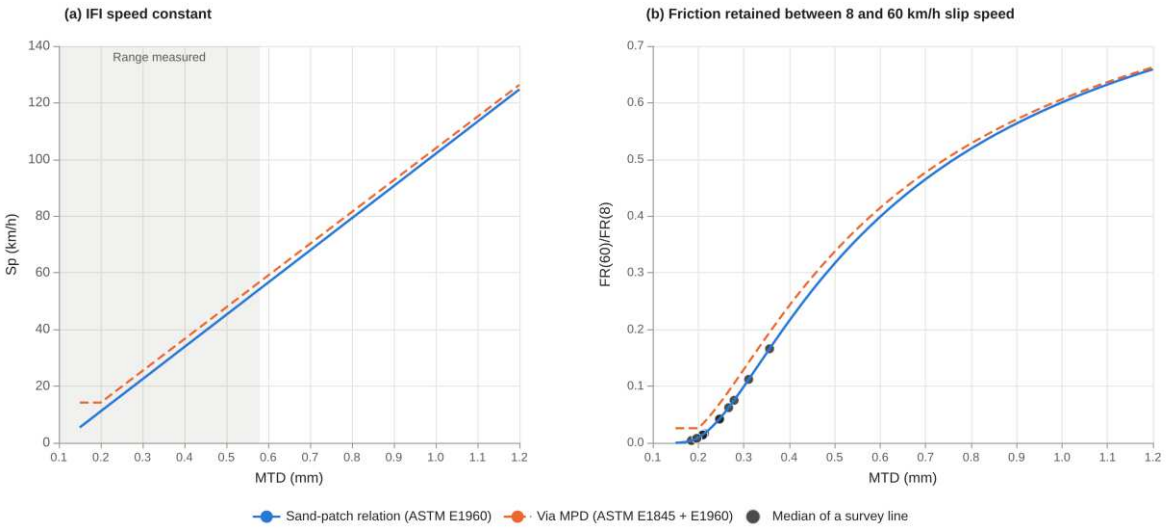


Fig. 6. (a) IFI speed constant as a function of sand-patch texture depth, from ASTM E1960 directly and through the MPD route. The shaded band is the measured range. (b) Fraction of friction retained between 8 and 60 km/h slip speed (Eq. 5); dots are survey-line medians.

3.4. Apparent polishing resistance of the existing surfaces

Inverting Eq. (6) for the measured mean SC (Table 5) yields apparent PSV values of 30–50 on the Teixeira lanes for TPL4–TPL6 traffic. On Axe 01 the values are 14–39 and on the loops 17–48. Aggregates used in bituminous surfacing generally have PSV well above 40. Values in the 14–35 range are therefore not credible as a description of the aggregate alone. The low friction on Axe 01 and on three loops is better explained by mechanisms that the equilibrium model does not represent. Candidates are a binder-rich or flushed surface with little exposed aggregate, which the low texture supports, contamination, summer temperature (the survey was in May) and measurement conditions. The equilibrium model is thus a reasonable description of the Teixeira lanes but not of the most deficient sites.

Table 5. Apparent PSV that reproduces the measured mean friction with Eq. (6) (mean of the two coefficient sets) for three traffic scenarios.

Run	Mean CFL	SC (Eq. 1)	PSV, TPL4	PSV, TPL5	PSV, TPL6
Teixeira Outbound Lane 1	0.332	0.296	30	33	40
Teixeira Outbound Lane 2	0.418	0.372	37	40	48
Teixeira Return Lane 1	0.373	0.332	33	36	43
Teixeira Return Lane 2	0.443	0.394	40	43	50
Axe 01 Outbound Lane 1	0.189	0.168	17	20	27
Axe 01 Return Lane 1	0.170	0.151	15	18	25
Axe 01 Outbound Lane 2	0.164	0.146	14	18	25
Axe 01 Return Lane 2	0.238	0.212	21	24	31
Axe 01 Outbound Lane 3	0.280	0.249	25	28	35
Axe 01 Return Lane 3	0.319	0.284	28	31	39
Sidi Abdellah Loop 1	0.271	0.241	24	27	34
Sidi Abdellah Loop 2	0.230	0.205	20	24	31
Sidi Abdellah Loop 3	0.429	0.382	38	41	48
Sidi Abdellah Loop 4	0.198	0.176	17	21	28

Traffic scenarios use the geometric mean of each class: 424, 949 and 2121 heavy vehicles per day and direction (Q = 0.9 × these values).

3.5. Polishing resistance required by traffic class

Fig. 7 and Table 6 give the PSV that keeps the equilibrium skid resistance at the investigatory level for each traffic class of the Technical document. For a dual-carriageway level (SC 0.35), PSV 35–38 suffices up to TPL5. TPL6 needs 45 and TPL7 about 60. For the urban level (SC 0.40), TPL6 needs 50 and TPL7 about 65. For bends and junction approaches such as the interchange loops (SC 0.45–0.50), even TPL5 requires 48–53. For TPL6 and above, the requirement exceeds 55–60, which few natural aggregates provide.

Table 6. PSV required for the equilibrium skid resistance to equal the investigatory level (Eq. 8; range over the two coefficient sets).

Traffic class	PL/day/direction	Q (cv/lane/day)	IL 0.35	IL 0.40	IL 0.45	IL 0.50
TPL3	150-300	191	34-34	39-39	44-44	49-49
TPL4	300-600	382	35-35	40-40	45-45	50-50
TPL5	600-1500	854	38-38	43-43	48-48	53-53
TPL6	1500-3000	1909	45-45	50-50	55-55	60-61
TPL7	3000-6000	4050	59-60	64-65	69-70	74-75

Class values use the geometric mean of the bounds (TPL7: 4500). TPL7 lies beyond the traffic range used to derive Eq. (6).

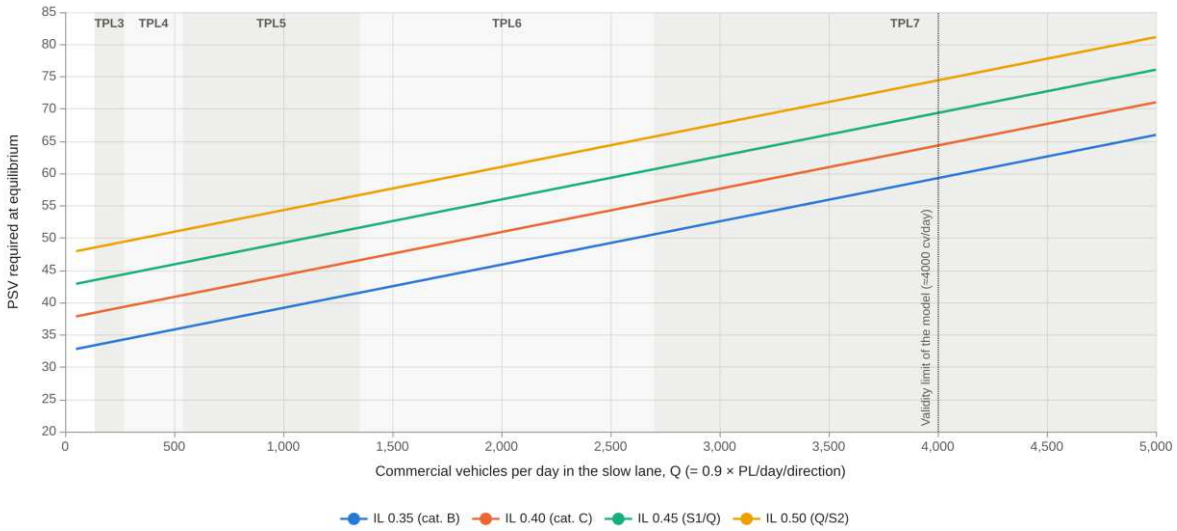


Fig. 7. PSV required at equilibrium as a function of slow-lane commercial traffic for four investigatory levels, with the traffic classes of the Algerian Technical document [1].

3.6. Functional life of a renewed wearing course

The Monte Carlo results (Fig. 8) show a sharp dependence on traffic. For TPL4, any aggregate with PSV ≥ 50 keeps the surface above the 0.35 and 0.40 levels for more than 20 years in most simulations. For TPL5, PSV 50 gives a median life of 17.5 years ($P(T_f \geq 8) = 87$ %) at the 0.40 level, and PSV 45 only 7.1 years ($P(T_f \geq 8) = 44$ %). For TPL6, the median life at the 0.40 level is 7.6 years ($P(T_f \geq 8) = 47$ %) with PSV 55 and 13.1 years ($P(T_f \geq 8) = 81$ %) with PSV 60. For TPL7, no PSV up to 65 gives a median life of more than 6 years at any level. On bends and junction approaches (0.45 level), the 8–10-year interval of the Technical document is reached with a probability above 75 % only for TPL4 with PSV ≥ 50, TPL5 with PSV ≥ 55 or TPL6 with PSV 65.

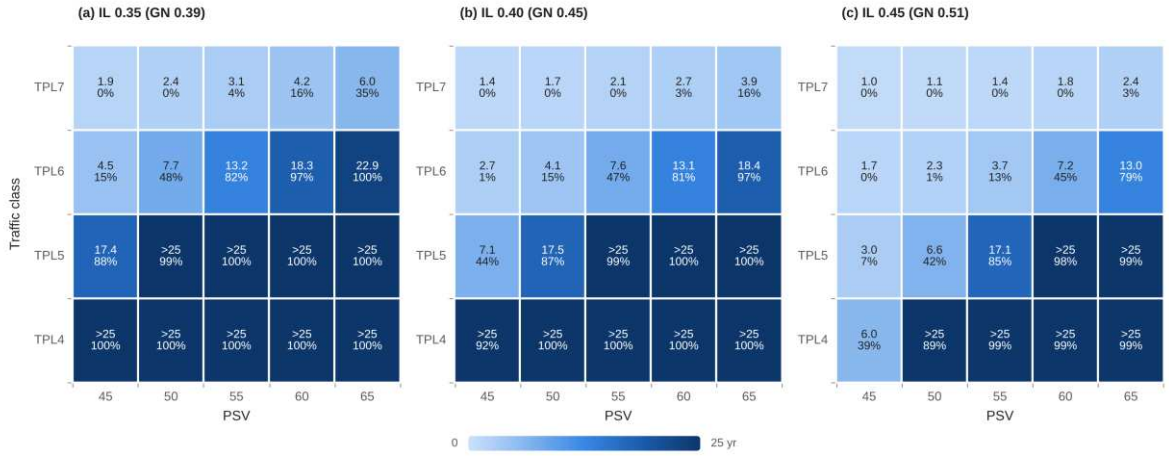


Fig. 8. Median functional life (years) and probability of reaching 8 years (percentage) of a renewed wearing course, by traffic class and PSV, for three investigatory levels. 20,000 Monte Carlo draws per cell.

Fig. 9 shows central trajectories. The early decrease is fast, but the crossing of the investigatory level is governed by the equilibrium reached under growing traffic, which is why the parameters of the early-life phase matter little. A one-at-a-time sensitivity analysis around TPL6, PSV 55 and SC 0.40 (base life 8.4 years; Table 7) confirms this. The initial GN and the time constant move the life by less than 1.5 years. Traffic within the class (4.0–16.8 years), PSV ±5 (4.5–14.4 years), traffic growth and the model error dominate.

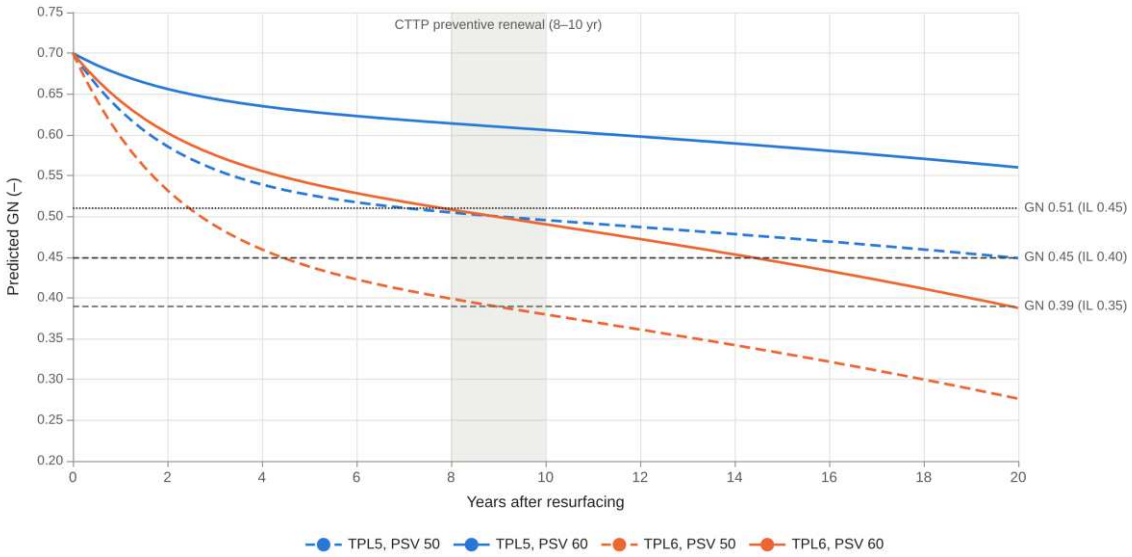


Fig. 9. Predicted GN after resurfacing for two traffic classes and two PSV values (central parameters: $GN_0 = 0.7$, τ = 2 years, growth 4 %/yr), compared with the benchmark levels and the 8–10-year renewal interval of the Technical document.

Table 7. One-at-a-time sensitivity of the functional life (TPL6, PSV 55, SC 0.40; base 8.5 years).

Parameter (low / high)	Life, low (years)	Life, high (years)	Range (years)
Lane traffic TPL6 upper / lower bound	4.0	16.8	12.9
PSV 50 / 60	4.5	14.4	9.9
Traffic growth 6 / 2 %/yr	6.3	15.8	9.5
Model error −0.03 / +0.03 (SC)	5.6	12.1	6.5
Time constant τ 1 / 3 yr	8.0	9.4	1.4
Initial GN0 0.5 / 0.9	8.1	8.8	0.7

Parameter (low / high)	Life, low (years)	Life, high (years)	Range (years)
Coefficient set S&H-2 / S&H-1	8.3	8.6	0.3

3.7. Traffic on representative Algiers roads

The 11 count stations span a wide range of traffic (Fig. 10; Table 8). Annual average daily traffic per direction ranges from 2,600 (CW133, Douera–Souidania) to 21,500 vehicles (CW122, Reghaia–RN24), and the estimated heavy-vehicle share from 1.5 % to 13 %. Peak-hour traffic is 6.5–8.5 % of daily traffic and night traffic 21–36 %, which indicates continuous urban use with no strong commuter peak. Four road types emerge. Type I comprises low-volume roads (< 4,000 vehicles/day/direction: CW133, CW214). Type II comprises medium urban roads (5,500–7,500: CW111, CW118, CW142, CW245). Type III comprises busy arterials (8,600–9,700: CW115, CW145). Type IV comprises heavily used roads (> 15,000: CW121, CW122). Translated into the Technical document's classes, the heavier direction of every station falls between below-TPL3 and TPL5 (130–1,450 heavy vehicles/day/direction). The busiest roads (CW121, CW122) reach TPL5 not through a high heavy-vehicle share but through very large total volumes.

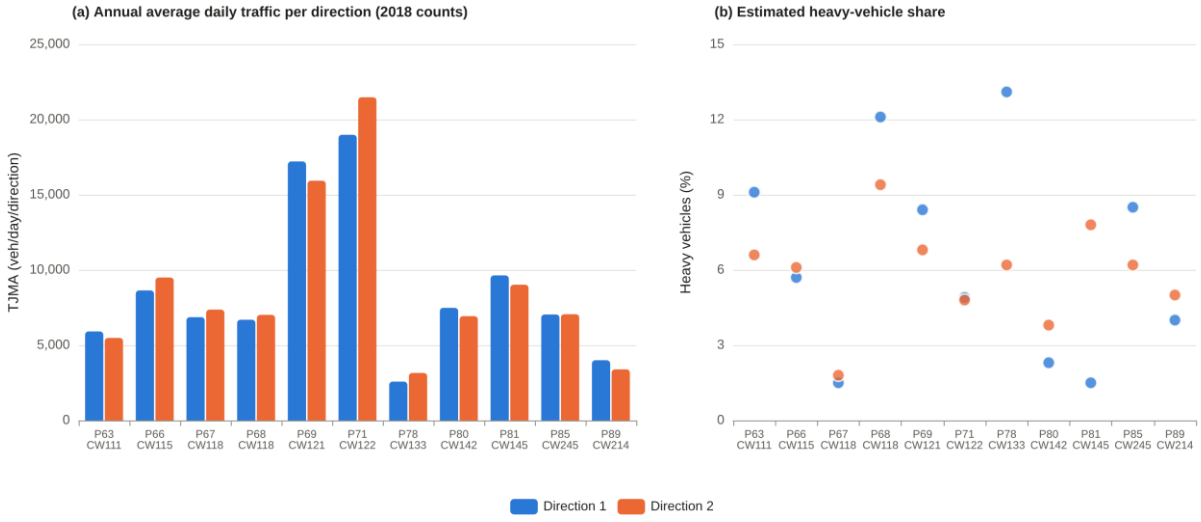


Fig. 10. Traffic at the 11 count stations (2018): (a) annual average daily traffic per direction; (b) estimated heavy-vehicle share (manual heavy-vehicle count divided by the automatic count; approximate, see Section 2.8).

Table 8. Traffic, cumulative loading after 10 years and predicted functional life at the count stations (heavier direction; PSV 50–60; IL 0.40; growth 2–6 %/yr; 8000 Monte Carlo draws).

Station	TJMA dir. 1/2	PL share 1/2 (%)	PL/day (class)	N_{HV} 10 yr (10^6)	NELV 10 yr (10^6)	TCE 10 yr (10^6)	T_f PSV 50	T_f PSV 55	T_f PSV 60	T_{str}
P-63 CW111	5912 / 5486	9.1 / 6.6	541 (TPL4)	2.2	33.7	1.4	>30	>30	>30	21
P-66 CW115	8639 / 9499	5.7 / 6.1	576 (TPL4)	2.3	43.1	1.5	>30	>30	>30	21
P-67 CW118	6863 / 7363	1.5 / 1.8	131 (<TPL3)	0.5	21.4	0.3	>30	>30	>30	22
P-68 CW118	6694 / 7015	12.1 / 9.4	811 (TPL5)	3.3	45.8	2.1	23.4	>30	>30	30
P-69 CW121	17209 / 15929	8.4 / 6.8	1453 (TPL5)	5.8	93.6	3.8	9.5	17.3	23.8	20
P-71 CW122	18983 / 21479	4.9 / 4.8	1024 (TPL5)	4.1	86.9	2.7	17.5	25.9	>30	26
P-78 CW133	2578 / 3156	13.1 / 6.2	338 (TPL4)	1.4	18.6	0.9	>30	>30	>30	29
P-80 CW142	7482 / 6928	2.3 / 3.8	260 (TPL3)	1.0	25.4	0.7	>30	>30	>30	22
P-81 CW145	9637 / 9021	1.5 / 7.8	706 (TPL5)	2.8	47.0	1.9	27.0	>30	>30	32

Station	TJMA dir. 1/2	PL share 1/2 (%)	PL/day (class)	N_{HV} 10 yr (10^6)	NELV 10 yr (10^6)	TCE 10 yr (10^6)	T_f PSV 50	T_f PSV 55	T_f PSV 60	T_{str}
P-85 CW245	7041 / 7061	8.5 / 6.2	601 (TPL5)	2.4	38.5	1.6	>30	>30	>30	35
P-89 CW214	4000 / 3393	4.0 / 5.0	169 (TPL3)	0.7	14.0	0.4	>30	>30	>30	29

T_f: median skid-resistance life (years), Eqs. (9)–(10) with Eqs. (11)–(16), ε = 0; >30 means beyond the 30-year horizon. T_{str}: structural reference life (years) implied by the Technical document for the traffic class. All roads are assumed to have two lanes per direction (λ_H = 0.9).

3.8. Service life as a function of traffic volume and heavy-vehicle share

Fig. 11 shows the median functional life of a new wearing course with PSV 55 at the 0.40 investigatory level as a function of traffic per direction and heavy-vehicle share. The life chart has a clear boundary. Below about 700 heavy vehicles per lane and day the equilibrium skid resistance stays above the investigatory level and the life exceeds 30 years. Beyond it, the life falls steeply: to about 10 years at 20,000 vehicles/day/direction with 10 % heavy vehicles, and to 4 years at 15,000 vehicles with 20 % heavy vehicles. Volume and composition can be traded against each other along lines of constant heavy-vehicle flow. A light-vehicle polishing weight of ε = 0.05 (Fig. 11b) shortens the life of high-volume, low-heavy-vehicle roads markedly, e.g. from 21 to 11 years at 25,000 vehicles/day/direction with 5 % heavy vehicles. This makes ε the key uncertainty for Algerian urban expressways, where light vehicles dominate.

Applied to the stations (Table 8), the model predicts skid-resistance lives beyond 30 years for Types I–III with PSV ≥ 55. With PSV 50, the heavier direction of CW121 has a median life of 9.5 years (P($T_f \geq 8$) = 63 %), and CW122 has 17.5 years. With PSV 50, the skid-resistance life is shorter than the structural reference life on four of the 11 roads (CW118 at P-68, CW121, CW122, CW145), but it is below 20 years only on CW121 and CW122, whose structural reference lives are 20 and 26 years. With ε = 0.05 the median life of CW122 falls from 25.9 to 15.2 years for PSV 55. For bends, loops and junction approaches (0.45–0.50 levels) the lives would be considerably shorter (Section 3.6).

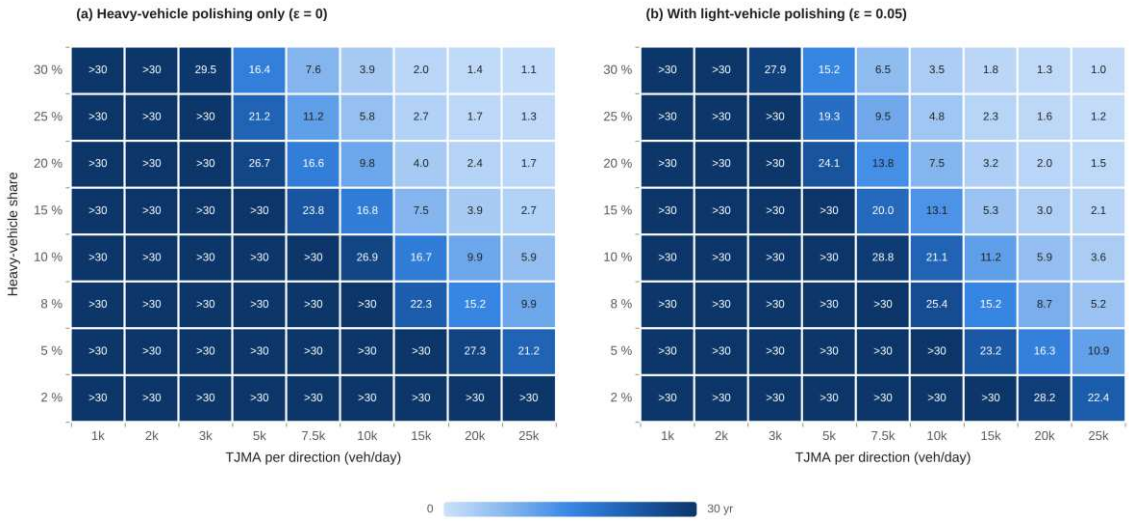


Fig. 11. Median functional life (years) of a new wearing course (PSV 55, IL 0.40) as a function of traffic per direction and heavy-vehicle share: (a) heavy-vehicle polishing only; (b) light vehicles weighted by ε = 0.05. Monte Carlo inputs as in Table 3; two lanes per direction.

3.9. Comparison with existing models

Table 9 compares the proposed model with deterioration and service-life models in the literature. The models fall into four families. Equilibrium polishing models [9] relate an asymptotic friction level to commercial traffic and aggregate polishing resistance. Network regression models [12, 13] relate measured friction to AADT, heavy vehicles and road features without explicit time. Time-dependent and survival models [11, 14] describe the decay of friction with time and the probability of crossing a threshold. Mechanistic polishing models [15] compute microtexture wear from contact mechanics and laboratory tests. Pavement-management systems combine several of these: HDM-4 [29] uses incremental skid and texture models driven by commercial and equivalent light vehicles, whereas the Algerian Technical document [1, 2] only accounts for structural damage through cumulative equivalent axles.

Table 9. Comparison of the proposed model with pavement surface deterioration and service-life models in the literature.

Model	Form and inputs	Data basis	Main assumptions / limitations	Suitability for Algerian urban expressways
Szatkowski & Hosking [9]	Equilibrium SFC = f(commercial vehicles/lane/day, PSV)	UK trunk roads, SCRIM	Steady state only; light vehicles ignored; < 4000 cv/day	Good for aggregate specification; needs time law and LV term
Echaveguren et al. [11]	Asymptotic decay with time; polishing equivalence factor for heavy vehicles; seasonal factors	≈1100 sections, Chile, SCRIM	Calibrated speed and temperature factors for Chile	Structure transferable; parameters need local calibration
Li et al. [14]	Hazard-based duration (survival) model of friction above thresholds; traffic and roadway features	Pennsylvania Interstate, annual data	Requires long annual series; censored data handling	Target model once monitoring data exist
Pérez-Acebo et al. [12]	Regression of friction on ln AADT with lane and section terms	Whole road network	Cross-sectional; no explicit time or PSV	Useful for network screening; no life estimate
Isasa et al. [13]	MSSC = 83.661 − 8.138 log AADT − 0.004 $AADT_{HV}$ (Eq. 18)	66 single-carriageway segments	R^2 = 0.44; cross-sectional; no time or PSV	Comparable trend (Fig. 12); offset needs local check
HDM-4 [29]	Incremental skid resistance driven by commercial vehicles; texture depth driven by equivalent light vehicles (1 HV = 10 ELV)	International, default coefficients	Defaults not calibrated for Algerian dense asphalt	Framework suitable; requires calibration factors
Kane et al. [15]	Mechanistic microtexture polishing (contact mechanics + wear law)	Laboratory (Wehner–Schulze)	Needs aggregate-specific tests; lab-to-field transfer	Supports PSV/aggregate selection research
CTTP Technical document [1, 2]	Cumulative 13-t axles TCE = TPL·365·C·A; structural fatigue design	Algerian traffic and materials	No surface (functional) deterioration; renewal at 8–10 years by rule	Official structural reference (Eq. 15)
Proposed model (this study)	$T_{SL} = \min(T_f, T_{tex}, T_{str})$; traffic volume, PL share, lane factors, growth, ε, PSV, speed gate	Literature parameters; Algerian traffic and condition data	Not yet calibrated on Algerian time series; ε uncertain	Directly linked to Technical document classes; calibration plan defined

Applied to the 11 stations, Eq. (18) and the equilibrium of the proposed model are strongly correlated (Fig. 12; Pearson $r = 0.95$, Spearman $\rho = 0.91$, $p < 0.001$). Both rank CW121 and CW122 as the most polishing-prone roads. The Isasa et al. model gives values 4–13 points lower (mean difference −8.2). This offset reflects different networks, devices and aggregates, and the PSV assumed in the proposed model. The

comparison model is also about twice as sensitive to traffic (slope 1.8). Because it uses total AADT, it attributes part of the friction loss to light vehicles. This is consistent with a positive ε in the proposed model.

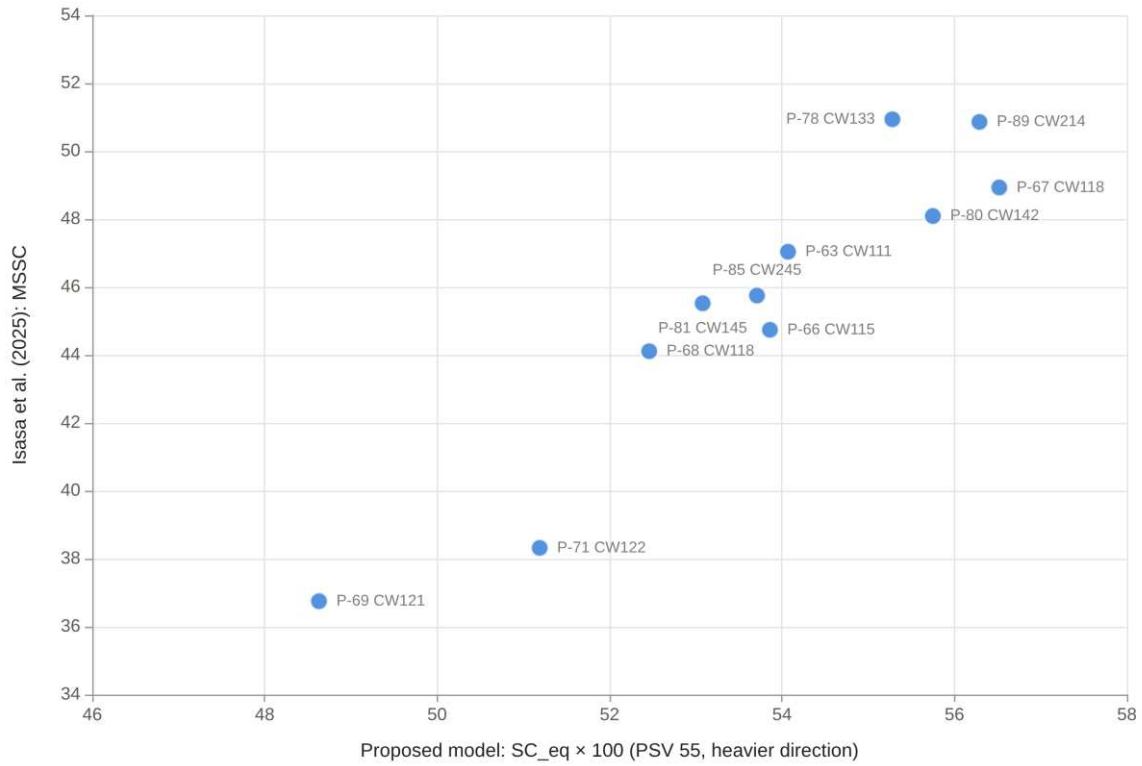


Fig. 12. Equilibrium skid resistance predicted for the 11 count stations by the proposed model (PSV 55, heavier direction) and by the network model of Isasa et al. [13] (Eq. 18).

3.10. Consistency checks and calibration design

Lane contrast. On Teixeira, lane 2 is more skid-resistant than lane 1 by 0.086 (outbound) and 0.070 (return) in CFL, i.e. 0.077 and 0.062 in SC. With $\lambda_1 - \lambda_2 = 0.8$ and $\varepsilon = 0$, the model attributes this contrast to about 1,440 and 1,170 heavy vehicles/day/direction. This corresponds to class TPL5, and it matches the busiest counted roads (CW121: 1,080–1,450). No traffic count is available on the Teixeira expressway to confirm this value. It is incompatible with the counts on CW133 (Douera–Souidania: 200–340 heavy vehicles/day/direction), the counted road nearest to the Teixeira field notes, which would require a heavy-vehicle share of about 40–55 %. Either the surveyed expressway is a different, busier road, or part of the lane contrast has other causes, such as different mix ages or light-vehicle polishing. The check cannot validate the model, but it shows that the measured lane pattern is quantitatively plausible under it.

Calibration design. The simulation study (Fig. 13; Table 10) shows how much monitoring the model needs. With two annual surveys the parameters are poorly identified. Hold-out R^2 is 0.10–0.50 and life predictions err by 4.7–7.4 years. With 20 sections surveyed for five years, R^2 reaches 0.78, the RMSE 0.050 approaches the noise floor (≈0.042), the 90 % intervals cover 88 % of observations, and life is predicted within about 1.5 years. Forty sections surveyed three times give a similar accuracy (2.0 years). The traffic slope b is then recovered with an interquartile range of about ±8–12 % of its true value, and the PSV-related intercept with a standard deviation of 1.3–1.5 PSV units. The light-vehicle weight ε remains the least identifiable

parameter (interquartile range 0.04–0.05 around a true value of 0.02). Separating light- and heavy-vehicle effects will therefore require sections with contrasting traffic composition, or lane-by-lane surveys.

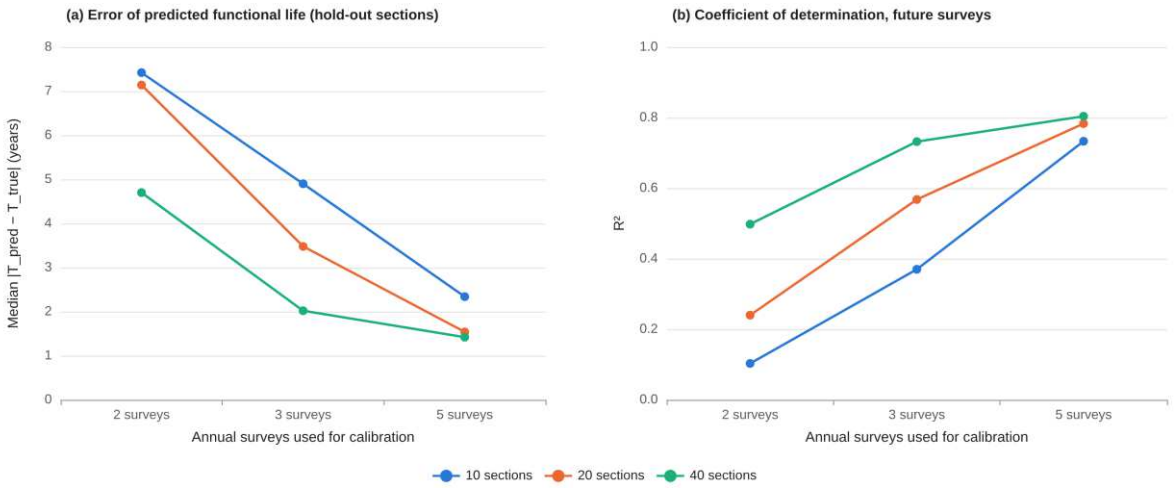


Fig. 13. Simulated calibration design: (a) median absolute error of the predicted functional life and (b) R^2 for future surveys of hold-out sections, as a function of the number of annual surveys and of sections used for calibration (60 replications per design).

Table 10. Predictive performance of the calibrated model in the simulation study (mean over 60 replications; hold-out sections, 8 future years).

Sections	Annual surveys	RMSE	MAE	Bias	R^2	90 % PI coverage	Life error (years)
10	2	0.088	0.069	-0.001	0.10	64 %	7.4
10	3	0.074	0.057	-0.018	0.37	73 %	4.9
10	5	0.055	0.044	-0.003	0.73	83 %	2.3
20	2	0.086	0.065	-0.021	0.24	70 %	7.1
20	3	0.063	0.050	-0.005	0.57	79 %	3.5
20	5	0.050	0.040	-0.005	0.78	88 %	1.5
40	2	0.064	0.050	-0.003	0.50	78 %	4.7
40	3	0.053	0.041	-0.003	0.73	86 %	2.0
40	5	0.047	0.038	-0.001	0.80	90 %	1.4

Synthetic data generated with the model itself (noise s.d. 0.03, section effect s.d. 0.03). The table assesses identifiability and survey effort, not the validity of the model structure.

4. Discussion

4.1. Why is friction so low?

Three findings frame the interpretation. First, friction is lowest where commercial traffic concentrates (lane 1 of the expressway) and on the loops, where vehicles brake and turn. This is the pattern expected from polishing [9, 16]. Second, the texture depth is uniformly very low, with no relation to the local friction. This suggests that the surface mixes provide little macrotexture from the start, or have lost it through densification or binder rise, independently of polishing. Third, on the arterial and three loops, the friction is too low to be explained by any plausible aggregate in the equilibrium model (apparent PSV 14–35). The study therefore suggests two co-existing mechanisms. Microtexture polishing explains the expressway pattern. A surface-composition problem (low texture, possible flushing or bleeding) is probably decisive on the worst sites. Cores and visual inspection would be needed to confirm the second mechanism; a core

was noted at PK 14+600 and PK 9+700 on Teixeira but no core data were available. The practical consequence is that a new wearing course with the same mix and aggregate would reproduce the problem.

4.2. Implications for the 8–10-year renewal interval of the Technical document

The Technical document's assumption that a wearing course lasts 8–10 years before renewal [1] holds, for skid resistance, only for moderate traffic (TPL4–TPL5) and adequate aggregate. For TPL6, keeping a 50 % or higher probability of 8 years at the urban level requires PSV ≥ 60. For TPL7, renewal intervals of 2–6 years would be needed even with PSV 65 (Fig. 8). On these roads, skid resistance rather than structural capacity governs the timing of surface renewal. A maintenance programme based on the 8–10-year rule alone would leave long sections below investigatory levels for several years. This conclusion is consistent with the measured state. On the Teixeira slow lanes the friction is already at or below the predicted equilibrium for TPL5–TPL6 traffic. The Technical document also contains no PSV or texture specification for the wearing course, even though its material sheets specify aggregate hardness (Los Angeles and micro-Deval) for the base courses [3].

4.3. Proposed condition indicators for Algerian wearing courses

On the basis of the results, Table 11 proposes indicators and provisional levels that could give operational content to the *condition indicators* of the Technical document. The levels are taken from international practice. They should be calibrated against Algerian accident and survey data before becoming regulatory.

Table 11. Proposed surface condition indicators, levels and requirements (provisional; based on external benchmarks and on this study).

Indicator / requirement	Proposed level	Use	Basis
Skid resistance, GN (10 m mean)	Investigate if < 0.39 (dual carriageway), < 0.45 (urban), < 0.51 (bends, loops, junction approaches)	Annual network survey; renewal trigger	[23], Eq. (1)
Macrotexture, MTD	Investigate if < 0.40 mm; < 0.25 mm treat as deficient	Survey with friction; high-speed roads	[24–26], Fig. 6
Initial texture of a new wearing course	MTD ≥ 0.6 mm at acceptance	Mix design and acceptance	[24]
Polishing resistance of the surfacing aggregate	PSV ≥ 50 (TPL4–TPL5), ≥ 55–60 (TPL6), ≥ 60–65 or high-friction surfacing (TPL7, loops)	Material specification	Table 6, Fig. 7
Early-life friction	GN ≥ 0.39 / 0.51 / 0.56 after 6 months by site class	Contract acceptance	[19]

4.4. Maintenance implications for the surveyed roads

Under the benchmarks of Table 2, the Axe 01 arterial (97 % of length below 0.39) and loops 1, 2 and 4 (100 % below 0.51) would require resurfacing or a texture-restoring treatment. For the loops, a high-friction surfacing would be justified by the required PSV. On Teixeira, the homogeneous sections of lane 1 below 0.30 (outbound 0.5–3.3 km and 5.1–5.4 km) should be prioritised. The sections of lane 2 above 0.45 could be scheduled later. Because texture is low everywhere, treatments that only restore microtexture (e.g. retexturing by shot-blasting) would not correct the high-speed deficit. A new wearing course with adequate texture would be needed on high-speed sections. These are planning indications drawn from a single survey; a current survey is needed before programming works.

4.5. Scientific contribution and practical use of the traffic-based model

The proposed model links three elements that are usually treated separately: the traffic classes of the national design Technical document, a literature polishing law, and an explicit split between light- and heavy-vehicle effects. Its main scientific contribution is to express the functional life of the wearing course in the same traffic variables that engineers already use for structural design (TJMA, heavy-vehicle share, lane factor, growth and cumulative loading). It also identifies which parameters matter (heavy-vehicle flow per lane, PSV, growth) and which can be fixed (initial friction, time constant). Unlike the Technical document's fixed 8–10-year rule, the model gives a road-specific renewal date with an uncertainty band. For Algerian urban expressways, its main limitation is the unknown weight of light-vehicle polishing (ε). Very high light-vehicle volumes are typical of these roads, so ε controls the predicted life of the busiest ones (Fig. 11b).

In practice, the model can be used in four ways. (i) At design, a life chart such as Fig. 11, combined with Table 6, gives the PSV and texture to specify for a given traffic so that the wearing course lasts at least the planned interval. (ii) For maintenance programming, each homogeneous section receives a predicted renewal year from its traffic and last measured friction, which allows multi-year budgeting. (iii) For network screening, sections where T_f is shorter than T_{str} identify roads where surface renewal, not strengthening, should be scheduled. (iv) For monitoring design, the calibration study indicates the survey effort needed: about 20 sections surveyed annually for five years, or 40 sections for three years, covering contrasting traffic compositions.

4.6. Measurement equipment and implications for monitoring

The equipment shown in Fig. 2 conditions both the interpretation of the present data and the design of future monitoring. The vehicle-integrated friction tester (Fig. 2a, b) records friction continuously at traffic-compatible speeds, which made it possible to survey 61.1 lane-km and to delineate 62 homogeneous sections from a single campaign. Its low slip speed, however, makes it essentially a microtexture indicator. On surfaces with a median texture depth of 0.23 mm, the CFL values of Table 4 therefore overstate the friction available to a braking vehicle at traffic speed (Fig. 6b), and the friction and texture indicators must be read together, as proposed in Table 11. The water-film depth and the test speed also influence the measured values; for repeated surveys they should be fixed and documented, and the device should be correlated with a reference SCRIM on common sections, so that the conversion of Eq. (1) is replaced by a local relation.

The pneumatic-tube counters (Fig. 2c, d) are portable, inexpensive and quick to install, which explains their use for short campaigns on the wilaya road network. They also have limitations that bear directly on the proposed model. Tubes laid across a multi-lane carriageway count all lanes together, so the lane factors λ_H and λ_L cannot be measured and had to be taken from the Technical document. Under the dense, slow and lane-changing traffic of urban roads, closely spaced axles may be merged, and the tubes wear quickly under heavy traffic. Moreover, without axle-based classification, the heavy-vehicle share depends on manual counts made during part of the day. Since the heavy-vehicle flow per lane is the most influential input of

the functional-life model (Table 7), the calibration programme of Section 4.5 should rely on classified, lane-by-lane counts, for example with inductive loops or piezoelectric sensors connected to the same type of counter, at the monitored friction sections.

4.7. Limitations

- The data come from one survey with no time series. The deterioration models are therefore taken from the literature and could not be calibrated locally. The functional-life results are conditional on the assumptions in Table 3.
- The exact device model and its calibration records, the test speed on two sites and the water-film depth were not documented in the data files. Seasonal and temperature corrections could not be applied, and the TRL conversion of Eq. (1) was not verified for the Algerian device.
- The chainage alignment between friction and texture data was assumed. Lane labels of the texture lines (P1/P2) on Teixeira could not be matched with certainty to the friction lanes.
- Traffic, age and composition of the wearing courses were unknown. Apparent PSV values are therefore scenario-dependent, and no causal attribution of the low friction can be proven without cores and PSV tests.
- The equilibrium model was derived from UK data under a different climate and with SCRIM measurements. Its use for TPL7 traffic extrapolates beyond its range.
- The IFI relations are used near the lower limit of their texture range. Friction-speed estimates for MTD below about 0.3 mm are indicative only.
- The traffic counts (2018) cover different roads from the friction survey. The heavy-vehicle shares rely on partial manual classification, lane distributions were assumed, and no vehicle speeds or axle loads were measured.
- The traffic-based model was checked for internal consistency and identifiability, but not validated against observed deterioration on Algerian roads. Its predictions are conditional on literature parameters until the proposed monitoring is carried out.

5. Conclusions

Continuous friction and sand-patch texture data from three road sites in the Algiers region were combined with literature deterioration models to assess the condition and the functional service life of asphalt wearing courses. The main conclusions are:

- Two thirds of the 61.1 lane-km surveyed (66.7 %) had friction below GN 0.39, the equivalent of the UK investigatory level for dual carriageways, and 84 % was below 0.45. The urban arterial and three interchange loops were critical (means 0.16–0.27).
- Macrotexture was very low everywhere (median 0.23 mm; no test above 0.60 mm). Through the IFI speed constant this implies a severe loss of wet friction with speed. Friction and texture depth were uncorrelated, so both must be measured.

- The equilibrium polishing model explains the expressway pattern (slow lane less skid-resistant) but not the lowest values. A surface-composition problem (low texture, possible flushing) probably adds to aggregate polishing on the worst sites.
- The PSV required to keep the equilibrium above investigatory levels rises from about 35–48 for TPL4–TPL5 to 45–55 for TPL6 and 60–70 for TPL7, depending on the site category.
- The 8–10-year wearing-course renewal assumed by the Algerian Technical document is achievable for skid resistance, at the 0.35–0.40 levels, only up to TPL5 with PSV ≥ 50. For TPL6 it needs PSV ≥ 60, and for TPL7 or demanding sites high-friction surfacings or shorter renewal intervals are needed.
- A traffic-based functional service-life model was formulated. It uses traffic volume, heavy-vehicle share, lane distribution, growth and cumulative loading, with an optional light-vehicle polishing weight, a speed-dependent texture gate and the Technical document's structural life. On 11 Algiers roads (2,600–21,500 vehicles/day/direction), it predicts skid-governed lives below 20 years only on the two busiest roads, and it agrees in ranking with an independent network model ($r = 0.95$).
- The model is not yet validated on Algerian deterioration data. A simulated calibration study shows that about 20 sections surveyed annually for five years (or 40 sections for three years) would allow life to be predicted within about 1.5–2 years. Sections with contrasting traffic composition are needed to quantify the polishing effect of light vehicles.
- Adding friction (GN) and texture (MTD) indicators, a minimum PSV by traffic class and an initial texture requirement to the Technical document would give operational content to its condition-based renewal rule.

Future work should establish repeated surveys on fixed sections, with classified traffic counts, to calibrate the time-decay model and the light-vehicle weight locally. It should also correlate the device with a reference SCRIM, test the PSV of Algerian surfacing aggregates, and relate friction and texture to wet-weather accident data.

Nomenclature

CFL / GN: longitudinal friction coefficient / Grip Number of the fixed-slip device (–)

SC: sideway-force (SCRIM) coefficient (–)

MTD, MPD: mean texture depth (sand patch), mean profile depth (mm)

S_p: IFI speed constant (km/h)

$FR(S)$: friction at slip speed S

PSV: polished stone value

Q: commercial vehicles per lane per day

PL: heavy vehicles (> 3.5 t) per day and direction

IL: investigatory level

T_f: functional life of the wearing course (years)

TPLi: traffic class of the Algerian Technical document

T, p: traffic per direction (TJMA, veh/day) and heavy-vehicle share

ε: polishing weight of a light vehicle relative to a heavy vehicle

NELV, TCE: cumulative equivalent light vehicles; cumulative equivalent 13-t axles

T_{SL}, T_{str}: functional service life; structural reference life (years)

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