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Fatigue life predictions for a European pavement test section subjected to individual and platoon truck configurations

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ABSTRACT

Truck platooning for the transportation of loads is a strategy recently proposed by the automotive sector to cope with traffic congestion, fuel consumption, and operational costs. This new form to configure trucks changes the typical solicitations the pavements structures are used to experience. In this sense, the research efforts of the pavement sector should be aligned with the automotive sector to propose road-friendly platoon configurations. This is one of the objectives of the European project ENSEMBLE. ENSEMBLE, as indicated by its acronym, works on Enabling Safe Multi-Brand platooning for Europe. In this context, the present study presents a real scale test done in the Applus IDIADA facilities to evaluate the fatigue behavior of a pavement structure subjected to individual and platoon truck configurations. The effects of parameters as traffic distribution along the year and along the time of the day, percentage of platoons, truck loads, number of trucks in platoon configuration, lateral wandering, and inter-truck distances were evaluated. The study's findings revealed that the reduced rest times between trucks in the platoon configuration reduce the recovery time of the asphalt layers, increasing the fatigue damage of the pavement at high temperature conditions. This underlines the need for further research to allow the proper implementation of truck platoons. For example, research is needed to define strategies to make truck platoon configurations more pavement-friendly and analyze the costs associated with the changes in the required road maintenance/rehabilitation treatments, among others.

Keywords: individual truck, platoon, fatigue life, pavement.

1. INTRODUCTION

Partially or fully self-driven trucks in platoon configurations are part of the most recent and innovative advances presented by automotive companies in the last decade [1]–[3]. These technologies seem to be capable of providing benefits in terms of reducing congestion for a better traffic flow, improving the braking/acceleration abilities of the vehicles, reducing fuel consumption, and more generally reducing operating costs of the vehicles and enhancing road safety [1], [2], [4]–[17].

However, platooning trucks introduce new traffic multi-load configurations with the following two characteristics: (1) reduced deviation of the lateral position of the vehicles forming the platoon and therefore load channelization [1], [4], [17]–[24] and (2) reduced inter-truck distances between the trucks in the platoon, which may hinder the self-healing capacity of asphalt concrete materials [4], [17], [22]. In this sense, a truck platoon deployment without precaution could accelerate pavement damage in terms of lower fatigue cracking/permanent deformation life [1], [4], [17], [20], [21], [23], [24] and lead to earlier rehabilitation/maintenance treatments [18], [23].

In this context, since 2018, the European Union has been developing a research project called ENSEMBLE. ENSEMBLE’s objectives are to pave the way for adopting multi-brand truck platooning in Europe to improve fuel economy, traffic safety, and throughput [2], [3].

ENSEMBLE is a European project co-funded under the Horizon2020 Research and Innovation Programme, grant agreement No 769115. This project is coordinated by the TNO (The Netherlands Organization), and associates main European trucks manufacturers (DAF, DAIMLER Truck, IVECO, MAN, SCANIA, VOLVO Group), the European Association of Automotive Suppliers (CLEPA), ERTICO (European Road Transport Telematics Implementation Coordination Organization, which is a link with the European Truck Platooning Community), and several research organizations: IDIADA, Gustave Eiffel University, KTH, and VU Brussel.

ENSEMBLE is composed of five work packages that integrate the different sectors related to the truck platoon development tasks in Europe. WP1 is related to Management, WP2 to Specification of a generic solution, WP3 to Platooning In-Vehicle Technology, and WP4, from which is part of this document, to Infrastructure, Logistics, and Impact analysis.

In this regard, the objective of this paper was to assess the effect that individual and platoon truck configurations can produce on the fatigue service life of a real scale pavement section located in the test track facilities of Applus IDIADA in Tarragona, Spain, which are commonly used for vehicle testing and development activities. The approach used in this project is based on an original fatigue model, developed by Homsí et al. [25]–[27] to consider the effects of multiple axle loads. This model was used to evaluate the fatigue life of the pavement structure for three potential scenarios of truck platooning, using a mechanistic-empirical approach based on the cumulative damage concept.

1.1.Cumulative damage

Miner's rule is the most popular and widely used damage model for materials [28]. As shown in Equation 1, Miner's rule states that damage (D) can be predicted by the linear accumulation of fatigue damage fractions due to each individual cycle, until failure occurs.

$$D = \sum_{i=1}^T \frac{n_i}{N_{fi}} \geq 1 \quad (1)$$

With n_i : the number of cycles at each stress amplitude level, N_{fi} : the number of cycles to failure for the stress amplitude of interest, and T : total number of load sequences.

For asphalt materials, different test protocols are used to define fatigue equations to determine the number of cycles to failure according to different strain/stress levels. In Europe, several test protocols are standardized by the European Committee for Standardization (CEN) under the EN 12697-24. New protocols have been recently defined to try to extend these fatigue equations to more complex loading conditions (non-sinusoidal signals, multiple loads). In the model proposed by Homsy et al. [18], new parameters are introduced, based on the shape of the strain signal obtained by the passage of multi-axle configurations.

1.2.Fatigue test protocols for asphalt materials in Europe

Based on EN 12697-24, there are six fatigue tests used in Europe to study the fatigue behavior of asphalt materials. Table 1 summarizes the test conditions applied in these six tests, as well as the fatigue equation proposed to fit the results. The different fatigue models are expressed by relationships between the applied cyclic strain or stress and the logarithm of the number of cycles to failure when specific temperature and frequency conditions are applied.

TABLE 1 Some standard protocols of testing in Europe according to EN 12697-24 [29].

Fatigue Test	Fatigue equation	Variables	Test conditions
Two points bending fatigue test on trapezoidal shaped specimen.	$\log(N) = a + \left(\frac{1}{b}\right) \log(\varepsilon)$	N : loading cycles. ε : relative maximum strain. a : intercept obtained by regression. $\frac{1}{b}$: fatigue curve slope.	<u>Load mode of testing</u> : displacement (3 strain levels). <u>Frequency</u> : 25 ± 1 Hz, sinusoidal in the upper part of the specimen with an amplitude = $\pm 5 \mu\text{m}$. <u>Temperature</u> : $10 \pm 1^\circ\text{C}$. <u>Failure criteria</u> : conventional (stiffness = 50% of initial value).
Two points bending fatigue test on prismatic shaped specimen.	$\ln(N_{ij}) = A_0 + A_1 \ln(\sigma_{jmax})$	N_{ij} : fatigue life specimen i for the tension level σ_{jmax} . A_0 : intercept obtained by regression. A_1 : fatigue curve slope. σ_{jmax} : maximum relative tension.	<u>Load mode of testing</u> : load (3 tension levels). <u>Frequency</u> : 25 ± 1 Hz, sinusoidal in the upper part of the specimen. <u>Temperature</u> : not specified, can be -20 to $30 \pm 1^\circ\text{C}$. <u>Failure criteria</u> : once reached a displacement = $280 \mu\text{m}$.
Three points bending fatigue test on prismatic shaped specimen.	$\varepsilon = k_1 * N^{k_2}$	ε : instantaneous strain or half of the cyclic amplitude for the strain function at cycle 100. k_1, k_2 : fatigue law coefficients obtained by regression. N : total number of cycles.	<u>Load mode of testing</u> : displacement (3 displacement levels). <u>Frequency</u> : 10 Hz, sinusoidal with a total amplitude $2D_0 = 80 \mu\text{m}$ to $350 \mu\text{m}$. <u>Temperature</u> : $20 \pm 1^\circ\text{C}$. <u>Failure criteria</u> : amplitude for cycle N is equal to half the amplitude of the cyclic load calculated for cycle 100, $(1/2 \varepsilon_c(100))$.

Four-point bending test on prismatic shaped specimens.	$\ln(N_{i,j,k}) = A_0 + A_1 * \ln(\varepsilon_i)$	N : fatigue life. i : specimen number. j : failure criteria selected. k : test conditions. ε_i : initial strain amplitude, measured at 100 cycle.	<u>Load mode of testing</u> : constant load or displacement (3 levels). <u>Frequency</u> : 0,1 to 60 Hz±0,1 Hz, sinusoidal. <u>Temperature</u> : 0 and 20±1°C. <u>Failure criteria</u> : conventional (stiffness = 50% of initial value)., but can be changed, should be indicated.
Indirect Tensile Test on cylindrical specimens.	$\log(N_f) = \log(k_\varepsilon) + n_\varepsilon * \log(\varepsilon_0)$ <u>Energy coefficient approach</u> : $\log(N_{f,w}) = \log(k_w) + n_w * \log(\varepsilon_0)$	N_f : loading cycles. $k_\varepsilon, n_\varepsilon$: regression parameters obtained from fatigue curve. N_f : loading cycles to fatigue for the resilience method. $k_\varepsilon, n_\varepsilon$: regression parameters obtained from fatigue curve for the resilience method.	<u>Load mode of testing</u> : constant load for the generation of a constant diametral stress tension. <u>Frequency</u> : 10Hz, indirect traction stress controlled, initial strain level in a range of 70 µm/m and 400 µm/m, 3 stress levels, load type haversine with loading time = 0.1 s and rest period = 0.4 s, <u>Temperature</u> : -10 to 30±0,5°C (10°C standard temperature). <u>Failure criteria</u> : cycles to fracture, but can be changed, should be indicated.
<u>Fatigue test</u> : Cyclic Indirect Tensile Test on cylindrical shaped specimens.	$\log(N_f) = \log(k_\varepsilon) + n_\varepsilon * \log(\varepsilon_0)$ <u>Energy coefficient approach</u> : $\log(N_{f,w}) = \log(k_w) + n_w * \log(\varepsilon_0)$	N_f : loading cycles. $k_\varepsilon, n_\varepsilon$: regression parameters obtained from fatigue curve. N_f : loading cycles to fatigue for the resilience method. $k_\varepsilon, n_\varepsilon$: regression parameters obtained from fatigue curve for the resilience method.	<u>Load mode of testing</u> : compression cyclic load for the generation of a uniform diametral stress tension. <u>Frequency</u> : 10Hz, sinusoidal without rest periods. <u>Temperature</u> : 20±0,5°C. <u>Failure criteria</u> : energy coefficient based in the dissipated energy approach.

Considering that the equations described in Table 1 do not consider the effect produced by multiple axle configurations, Homsí et al. [25]–[27], [30] proposed the fatigue model shown in Equation 2. Homsí's model is based on the laboratory reproduction of 12 synthetic strain signals obtained from the real strain signals obtained from the Accelerated Pavement Testing facility of IFSTTAR-Gustave Eiffel University (from the French acronym: French Institute of Science and Technology for Transport, Development, and Networks) under single, tandem and tridem axles. The laboratory test used to reproduce the 12 synthetic signals was the 2-point bending fatigue test, on trapezoidal specimens conditioned at 20°C (common European fatigue test standardized as UNE EN 12697-24 [22]), which was adapted to apply frequencies ranging from 8.33 Hz to 40 Hz and strain levels ranging from 47 µm/m to 550 µm/m. The fatigue failure criterion used to calibrate the model considers the point when there is a 50% reduction in the initial stiffness value of the material.

$$\log(N_f) = a \log(\varepsilon) + b * \log(Np) + c * \hat{A}n + d * \bar{D} + e \quad (2)$$

[25]–[27], [30]

Where (see Figure 1), ε : strain intensity (peak strain level) produced by the passage of the reference axle (tridem axle in the example of Figure 1), Np : number of peaks of the strain signal (1 for single axles, 2 for double axles and 3 for tridem axles), $\hat{A}n$: positive area under the loading signal in the transversal/longitudinal direction divided by the peak strain and its duration, and \bar{D} : Duration of the loading signal divided by the number of peaks (in seconds).

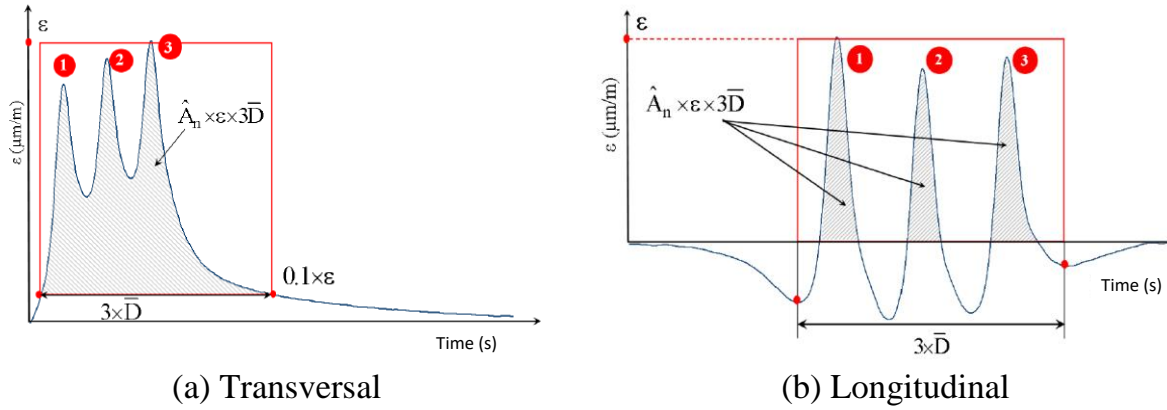


FIGURE 1 Example of parameters used to characterize the transversal/longitudinal strain signals of a tridem axle (reprinted from [25]).

2. FULL SCALE EXPERIMENT

2.1. Pavement section and instrumentation

The test section used in the study was located in the facilities of the automotive company IDIADA, in Tarragona, Spain. The pavement structure consisted of 3 asphalt layers: a 4 cm thick wearing course, a 6 cm thick binder course, and a 15 cm thick base course. According to the standard UNE EN 13108-1, the types of asphalt mixture for each layer are respectively: asphalt concrete mixture with 11 mm maximum particle size used for surface layers (AC11 surf (D12)), semi-dense graded asphalt concrete mixture with 20 mm maximum particle size (AC 22 S (S-20)), and coarse graded asphalt concrete mixture with 22 mm maximum particle size (AC 22 G (G-20)). The mixtures were manufactured with a polymer-modified binder type PMB 45-80/65 according to the UNE-EN 14023, reaching densities of 2.38 to 2.39 g/cm³ and air voids of 4.7% to 6.8%.

As shown in Figure 2, the section was instrumented with an array of 24 strain gauges type KM-100HAS Tokyo Sokki Kenkyujo, placed at 0.85m, 1.05m, and 1.25 from the edge of the right lane. 12 strain gauges (6 longitudinal and 6 transversal), were placed at the bottom of the binder course and 12 other gauges at the bottom of the base course. Thermocouples were also installed at the bottom of each asphalt layer, to measure the temperature conditions during the tests.

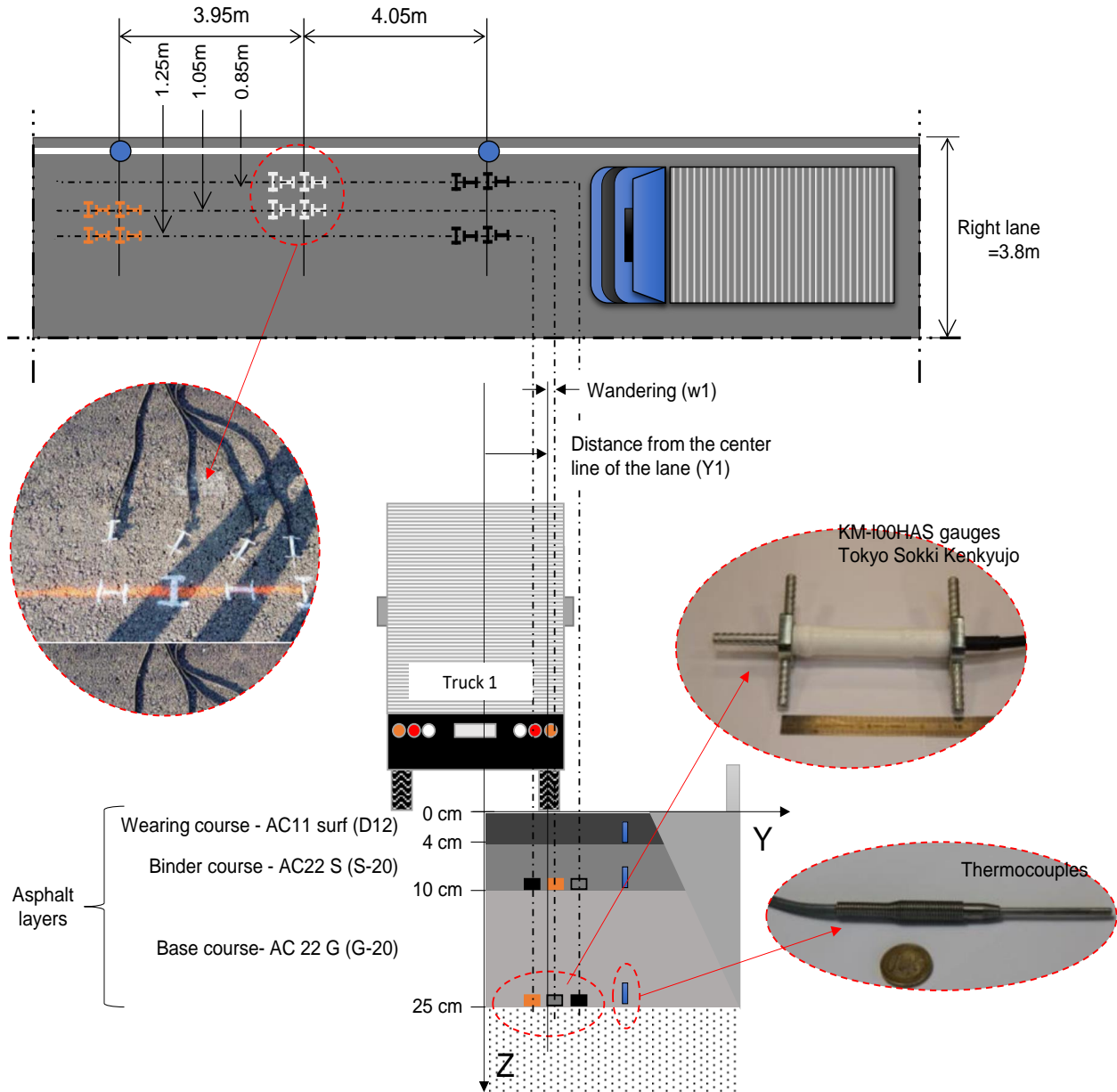


FIGURE 2 Schema of the pavement structure and instrumentation (not to scale).

2.2. Test protocol

The objective of the tests was to compare the pavement response under individual trucks and trucks in platoon configuration. Two test campaigns were performed, one in the winter, and one in the summer, to cover both cold and hot temperature conditions. The different test conditions are summarized in Table 2 and Figure 3, and include:

- i. two test campaigns, one done in the winter and the other in the summer,
- ii. 20 cm of lateral deviation (wandering) for the first four strain signals and addition of 4 extra strain signals with a lateral deviation (wandering) increased to 40 cm during the summer campaign (see Figure 3b),
- iii. lateral offset of 0 cm from the centerline of the lane (see Figure 3b),

- iv. inter-truck distances adjusted to a time gap of 0.8s,
- v. four truck speed values,
- vi. individual and platoon truck load configurations.

TABLE 2 Parameters evaluated in the experimental program.

Parameter	Characteristics
Pavement responses: horizontal strains	<p>Depth of measurement:</p> <ul style="list-style-type: none"> 10 cm (4cm of a wearing course + 6cm of a binder course). 25 cm (4cm of a wearing course + 6cm of a binder course + 15 cm of a base course). <p>Direction of measurement:</p> <ul style="list-style-type: none"> Longitudinal. Transversal.
Lateral deviation (wandering)	<p>20 cm: 4 strain signals for winter/summer and individual/platoon, at each test speed.</p> <p>40 cm: additional 4 strain signals (8 strain signals in total) for platoon and summer at each test speed.</p> <p>Lateral deviation (wandering) between platoons and between trucks.</p> <p>Values measured with the laser system shown in Figure 4.</p>
Lateral offset	0 cm from the center line of the lane.
Inter-truck distance	<p>Adjusted to a time gap of 0.8 s between trucks.</p> <p>Values measured with the laser system shown in Figure 4.</p>
Campaigns and truck configurations	<p>Winter:</p> <ul style="list-style-type: none"> 11 of January 2020: <ul style="list-style-type: none"> Configuration: Individual trucks Temperature: 10.3°C and 11.3°C respectively at 25cm and 10cm depth from the pavement surface. 12 of January 2020: <ul style="list-style-type: none"> Configuration: Platoon. Temperature: 8.3°C and 6.1°C respectively at 25cm and 10cm depth from the pavement surface. <p>Summer:</p> <ul style="list-style-type: none"> 29 of August 2020: <ul style="list-style-type: none"> Configuration: Individual trucks Temperature: 27.5°C and 25.9°C respectively at 25cm and 10cm depth from the pavement surface. 30 of August 2020: <ul style="list-style-type: none"> Configuration: Platoon. Temperature: 25.7°C and 25.0°C respectively at 25cm and 10cm depth from the pavement surface.
Truck load	≈48 ton, fully loaded semitrailer truck limits defined by the EU (see details per axle type in Figure 3a).
Truck speed	<p>40, 60, 70 and 80 km/h (EU speed limits defined for heavy trucks circulation).</p> <p>Values measured with the laser system shown in Figure 3c.</p>
Number of passages	<p>Winter:</p> <ul style="list-style-type: none"> Individual configuration: 4 speeds x 2 repetitions x 3 trucks = 24 passages. Platoon configuration: 4 speeds x 5 repetitions = 20 passages. Total passages = 44. <p>Summer:</p> <ul style="list-style-type: none"> Individual configuration: 4 speeds x 2 repetitions x 3 trucks = 24 passages. Platoon configuration: 4 speeds x 5 repetitions = 20 passages. Total passages = 44

Three 5-axle human-driven semi-trailer trucks, fully loaded at their maximum legal load in Europe (40 tons), were used for each test campaign. The main characteristics of the vehicles used are shown in Figure 3a. The use of human-driven trucks following platoon truck configurations is the cause of the variation in the loads per truck and test campaign. Figure 4 shows the laser system used to measure the ability of the human drivers to follow platoon truck configurations. The parameters measured by the laser system were the truck speed, lateral deviation (wandering), and inter-truck distances.

The tests were performed first with each individual truck and then with the platoon configuration for each test condition. The longitudinal/transversal strains were measured at the bottom of the binder course and base course during each truck passage. Four strain signals per truck speed were selected to analyze the fatigue behavior in the first lateral wandering interval. And four additional strain signals were added to the analysis of the summer campaign to study the effect of increasing the wandering.

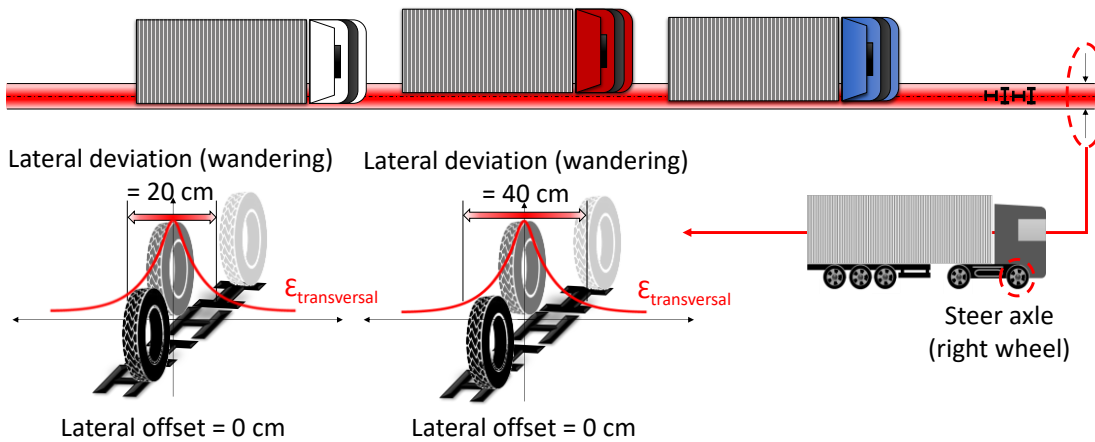
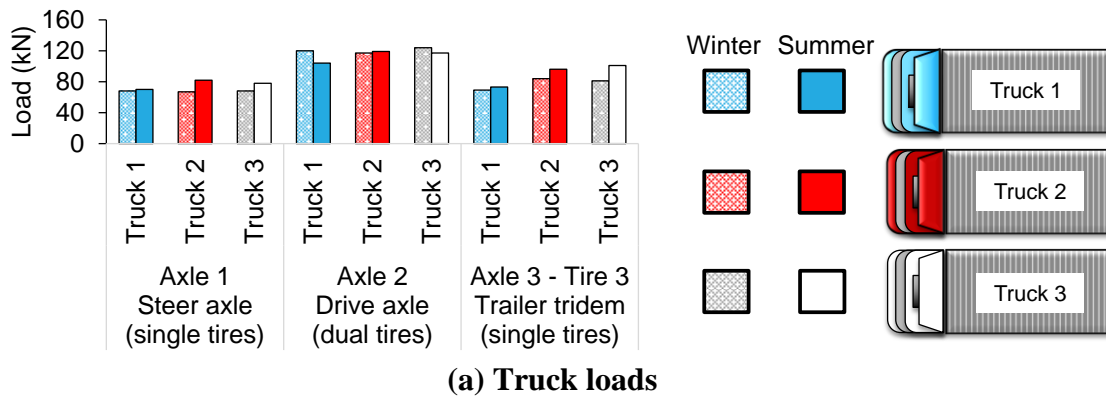


FIGURE 3 Truck-loads, lateral deviation (wandering) and laser system.

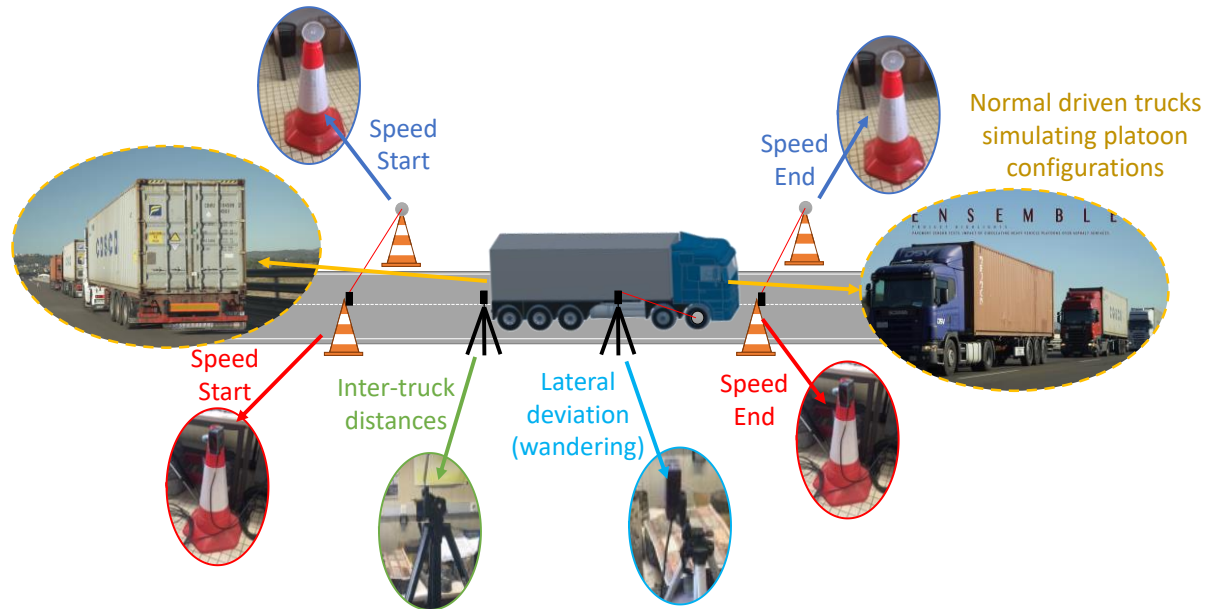


FIGURE 4 Laser system for monitoring truck speeds, and longitudinal and lateral positions

3. EXAMPLES OF MEASURED STRAIN SIGNALS

Figure 5 presents examples of longitudinal and transversal strain signals measured at the bottom of the base course, at 25cm depth from the pavement surface, during the winter and summer test campaigns. The figure compares signals obtained for an individual truck, and the platoon of 3 trucks, at a speed of 40km/h. The selected signals correspond to truck passages where the lateral wandering is close to 0, which means that the truck wheels are centered on the position of the strain gauges. For this position, the tensile strains recorded by the gages are maximum. The following observations can be made on these strain signals:

- Strains measured in summer (at temperatures between 25.0°C and 27.5°C) are much higher than the strains measured in the winter (at temperatures between 6.1°C and 11.3°C)
- The shape of the longitudinal and transversal strain signals is very different. The longitudinal signals present alternatively strains in compression (negative) and in extension (positive). The transversal strains are only in extension.
- The tensile strain values are significantly higher in the transversal direction due to the single wheels of the trailer tridem axles of the semitrailer trucks commonly used in Europe at present [31]. This could explain the predominant emergence of longitudinal cracking patterns on the pavement surface.
- The transversal strain signals present delayed deformations that are only slowly recovered after the passage of the vehicles due to the viscoelastic behavior of asphalt materials. These delayed deformations increase with temperature (summer conditions) and when inter-vehicle distance is small (platoon configuration).

Considering that the main objective of this work is the study of the fatigue cracking phenomena under individual and platoon truck configurations, in the next part of the paper, the analysis will focus only on the transversal strain signals, which generate the highest tensile strains, with values slowly returning to zero and possibly some permanent deformations.

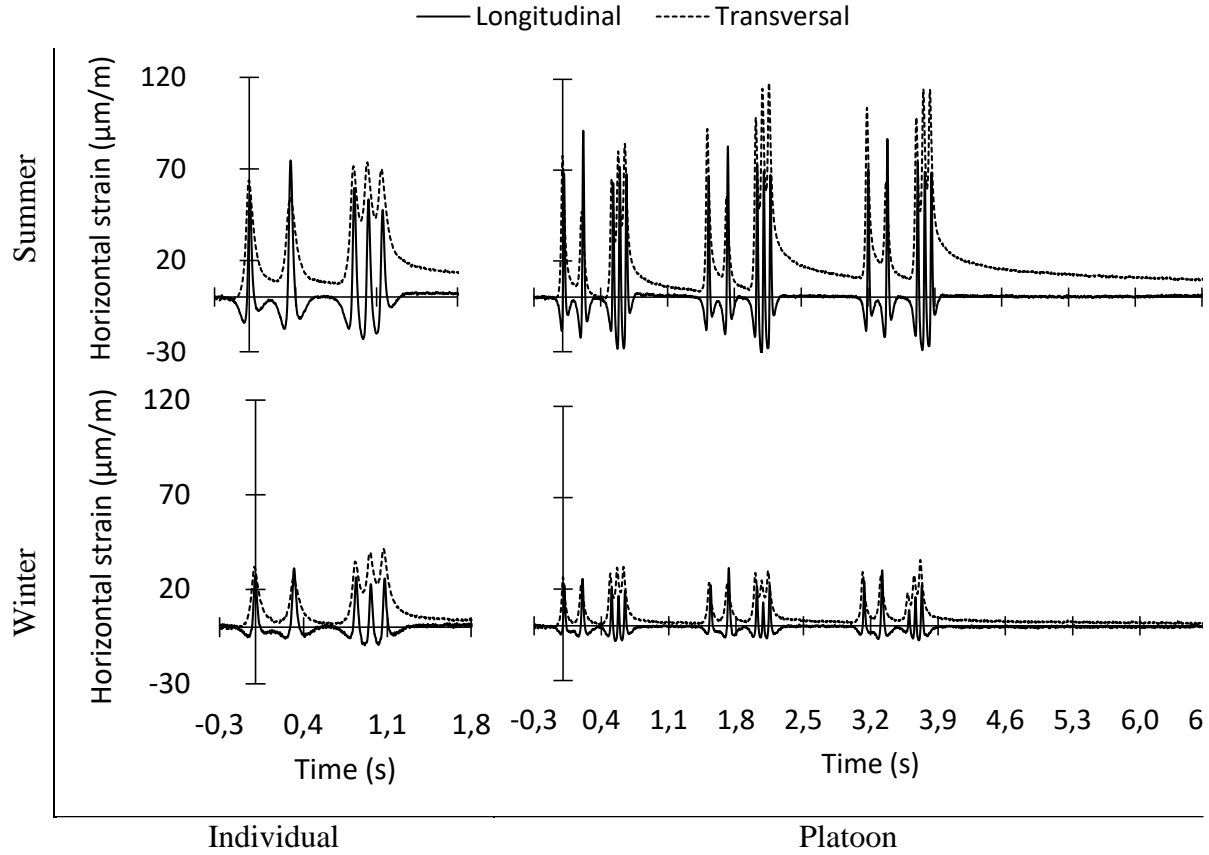


FIGURE 5 Examples of longitudinal and transversal strain signals obtained at 25 cm depth from the pavement surface (at the bottom of the base course) for a test speed of 40 km/h.

4. DATA TREATMENT – CALCULATION OF PAVEMENT DAMAGE

4.1 Definition of fatigue damage and calculation of the Coefficient of Aggressiveness

The concept of Coefficient of Aggressiveness (CA) of a vehicle, used in the French pavement design method, is introduced to evaluate and compare the fatigue damage produced by the different vehicle configurations.

In the case of fatigue damage, the Coefficient of Aggressiveness of a vehicle is defined as the α -factor (in percentage) of the ratio between the fatigue damage produced by a given truck and the damage produced by the equivalent standard axle (ESAL), which is a single axle with dual wheels, loaded at 130 kN in the French pavement design method. The value of the α -factor corresponds to the accepted level of damage corresponding to the end of service life of the pavement (20% in this paper case study). According to this definition, the CA of a truck can be defined by Equation 3.

$$CA_{truck} = \alpha * \frac{d_{truck}}{d_{ESAL}} = \alpha \sum_{i=1}^n \left(\frac{d_{Axle_i}}{d_{ESAL}} \right) \quad (3)$$

Where, d_{truck} is the fatigue damage produced by the whole truck, d_{ESAL} is the fatigue damage produced by the equivalent standard axle (130 kN axle), d_{Axle_i} is the damage produced by the i^{th} axle of the truck and n is the number of axles of the truck.

The concept of cumulative damage is used for the calculation of the fatigue damage d produced by a single load. With this approach, the elementary damage produced by one load can be simply defined by Equation 4.

$$d = \frac{1}{N_f} \quad (4)$$

Where, N_f is the number of load cycles leading to failure, defined using the fatigue model.

In this study, in order to consider complex strain signals, the number of cycles to failure N_f due to each truck axle (steer axle, driven axle, and trailer tridem) was calculated using the fatigue model for multiple axle loads proposed by Homsy (Equation 2). This equation is based on the shape parameters of the strain signals registered from the passage of isolated single, tandem and tridem axles in the Accelerated Pavement Testing (APT) facilities of Gustave Eiffel University.

In the case of the strain signal corresponding to the reference 130 KN axle, as this signal was not measured, it was obtained by modeling, using the multilayered elastic software ALIZE, for the same pavement structure, same temperature, and loading speed conditions.

From all the experimental data, only four-strain signals where the lateral wandering values between passages for the individual trucks and platoon configuration was less than 20 cm for both test campaigns were considered. In the case of the summer campaign, four additional strain signals with an increased lateral wandering (40 cm) were added to compare the effect of this increased lateral wandering.

Finally, to evaluate the fatigue life and fatigue damage corresponding to different traffic scenarios, the approach of the French pavement design method was followed. In this approach, after determining the Coefficient of Aggressiveness of each truck (CA_{truck}), according to equation 4, a mean coefficient of aggressiveness corresponding to the total cumulative traffic called CAM is determined according to Equation 5.

$$CAM = \frac{1}{N_{truck}} \sum_{j=1}^{N_{truck}} CA_{truck_j} \quad (5)$$

Where, N_{truck} is the total number of trucks considered, and CA_{truck_j} the coefficient of aggressiveness of truck j . With this definition, the CAM value can also be defined as the coefficient which is used to convert the number of trucks in a traffic N_{truck} into the corresponding number of ESALs, designated by NE Equation 6).

$$NE = CAM \times N_{truck} \quad (6)$$

4.2 Traffic scenarios for the calculation of pavement fatigue life.

To evaluate the impact of different proportions of platoons in the heavy vehicle traffic, five different traffic scenarios (shown in Figure 6) have been considered:

- The reference scenario represents traffic with no platoons and with a lateral wandering of 20 cm
- Scenario 1 represents traffic with 100% of platoons in the winter and no platoons in the summer, with the same lateral wandering of 20 cm.
- Scenario 2 represents traffic with 100% of platoons in the summer and no platoons in the winter, with the same lateral wandering of 20 cm.
- Scenario 3 represents traffic with 100% of platoons during the whole year, with the same lateral wandering of 20 cm.
- Scenario 4 represents traffic with 100% of platoons during the whole year, but with an increased lateral wandering of 40 cm











Reference	Campaign: Winter, Wandering = 20 cm, Conf: Individual (0% platoon penetration) $ADT = ADT_{Jan}$	
	Campaign: Summer, Wandering = 20 cm, Conf: Individual (0% platoon penetration) $ADT = ADT_{Aug}$	
Scenario 1	Campaign: Winter, Wandering = 20 cm, Conf: Platoon (100% platoon penetration) $ADT = ADT_{Jan}$	
	Campaign: Summer, Wandering = 20 cm, Conf: Individual (0% platoon penetration) $ADT = ADT_{Aug}$	
Scenario 2	Campaign: Winter, Wandering = 20 cm, Conf: Individual (0% platoon penetration) $ADT = ADT_{Jan}$	
	Campaign: Summer, Wandering = 20 cm, Conf: Platoon (100% platoon penetration) $ADT = ADT_{Aug}$	
Scenario 3	Campaign: Winter, Wandering = 20 cm, Conf: Platoon (100% platoon penetration) $ADT = ADT_{Jan}$	
	Campaign: Summer, Wandering = 20 cm, Conf: Platoon (100% platoon penetration) $ADT = ADT_{Aug}$	
Scenario 4	Campaign: Winter, Wandering = 40 cm, Conf: Platoon (100% platoon penetration) $ADT = ADT_{Jan}$	
	Campaign: Summer, Wandering = 40 cm, Conf: Platoon (100% platoon penetration) $ADT = ADT_{Aug}$	

FIGURE 6 Scenarios of analysis.

These traffic scenarios have been applied to calculate the fatigue life of the pavement structure of the full-scale experiment (Figure 2). For these fatigue life calculations, typical data corresponding to heavy traffic roads, category T00 according to EU definitions were used:

- An Average Daily truck traffic (ADT, for the weighing highways in Spain where the experiment took place) of 15951 for winter and 28587 for summer was used, corresponding to a two-way road with light and heavy vehicles, according to the traffic database of the Spanish Road and Highway Administration [32].
- The corresponding cumulative traffic was then calculated using Equation 7.

$$N = T * C * L * D * 365 * ADT \quad (7)$$

With, T : Percentage of trucks in the ADT, January: 18% and August: 13% [32]. C : Annual traffic growth factor (Equation 4, for g : annual traffic growth rate, January: 3,3% and August: 3,1% [32]). D and L : Direction Distribution Factor and Lane Distribution Factor, which were considered 50% and 85% for a two-way road with three lanes by traffic direction, according the Spanish Order FOM/3460/2003 [33].

$$C = \frac{(1 + g)^p - 1}{g} \text{ for } g \neq 0 \quad (8)$$

5. PAVEMENT DAMAGE AND PAVEMENT FATIGUE LIFE RESULTS

5.1. Winter tests campaign

As described before, the equation proposed by Homsy [25]–[27], [30] for multiple axle configurations was used to determine the number of cycles to fatigue for each truck under each load configuration and test campaign. The different parameters of the fatigue model obtained for each axle (Axle 1: single wheels, Axle 2: dual wheels, and Axle 3: tridem with single tires), for each truck, either in single truck configuration or in platoon configuration, are shown in Figure 7.

For this winter test campaign, there is no significant difference between the model parameters obtained for the single trucks and the platoon, probably because for the temperature range corresponding to this campaign (between about 6 and 11 °C), the behavior of the pavement is relatively elastic, and there is no significant effect due to the application of multiple truck loads in a short time interval.

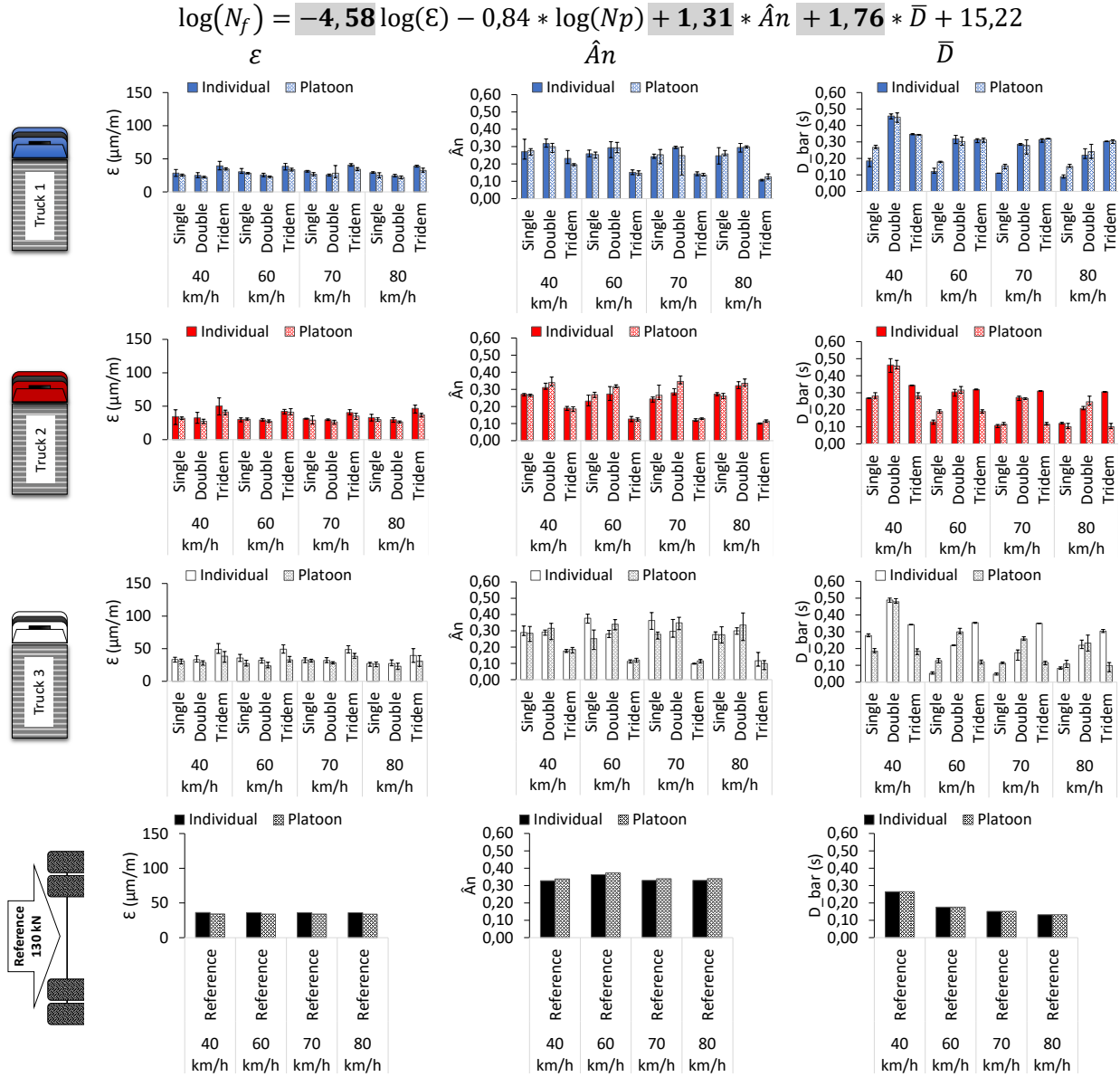


FIGURE 7 Fatigue parameters of the strain signals for the winter campaign (tension is considered positive). Fatigue coefficients obtained from [25]–[27], [30]. Single: steer axle, Double: driven axle and Tridem: trailer tridem axle.

The relationship between the damage obtained from each axle and the equivalent standard axle (130 kN) (which represents the aggressiveness of each individual axle) is shown in Figure 8. This figure shows that the tridem axles cause the highest damage, as was expected. The corresponding coefficients of aggressiveness for entire trucks (CA_{truck} , Equation 3), calculated for a level of damage of 20% of the pavement, are also shown in the same figure. The results indicate that:

- The CA_{truck} values are a little higher for truck 2 and truck 3 (for the individual trucks), which can be due to probably the natural variability of the test (temperature, position of the wheels, differences in axle loads).

- There is no clear difference between the CA_{truck} values obtained for the individual trucks and for the platoons. In some cases, for trucks 2 and 3, the individual trucks are more aggressive than in the platoon. This means that for cold temperatures (here around 10°C), platooning does not seem to create more fatigue damage than individual trucks (for the configurations considered in this experiment).

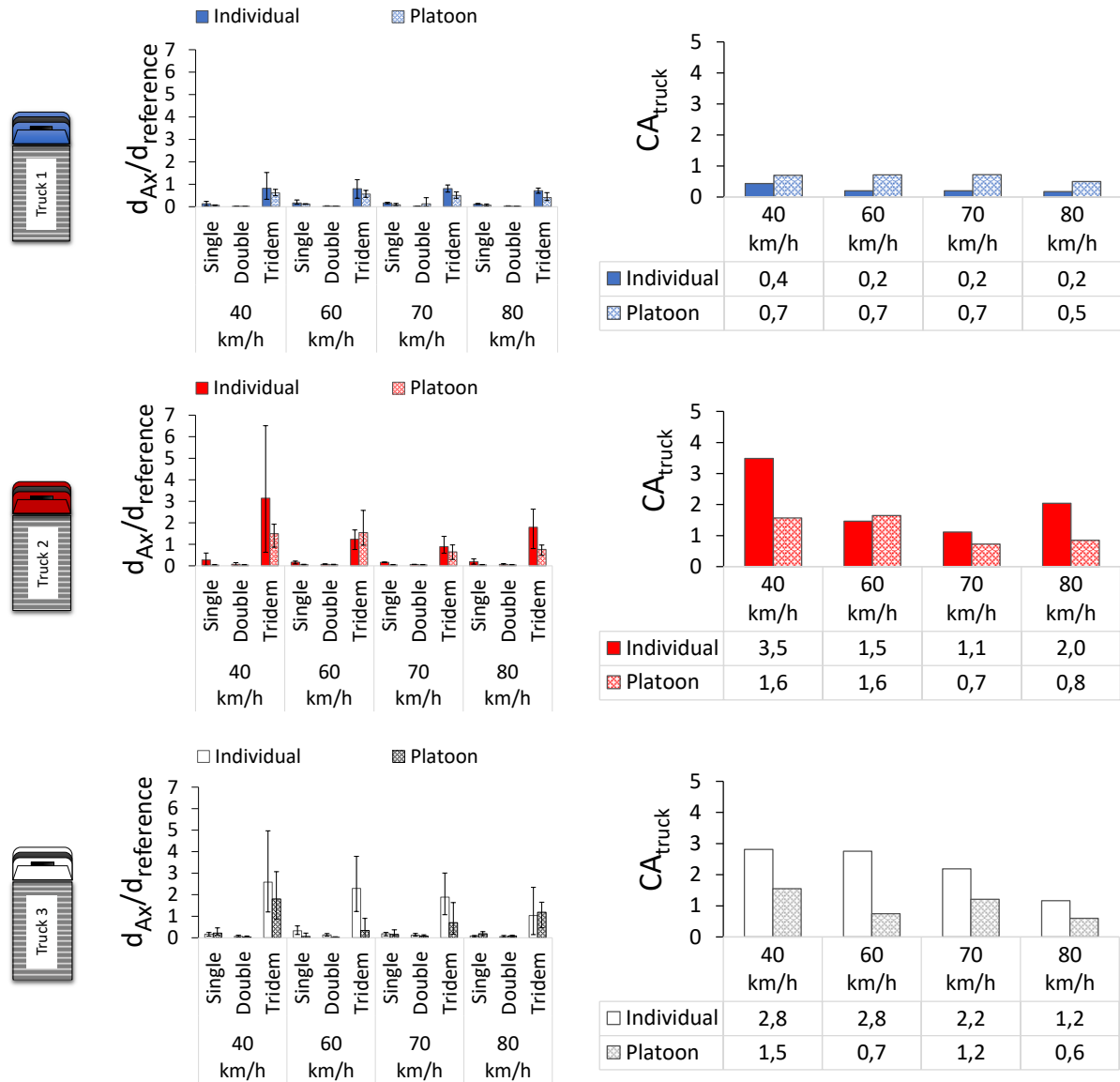


FIGURE 8 Values of fatigue damage induced by each truck axle (relatively to the reference 130 kN axle), and CA_{truck} values of the different trucks, for the winter test campaign.

5.2. Summer campaign

Figure 9 shows, for the summer campaign, the values of the parameters of the fatigue model of Homsy, for each truck and each axle, under both individual and platoon load configurations. Understanding that the positive or negative sign of each coefficient in the multi-axle fatigue equation indicates an increase or decrease in the number of cycles to fatigue, the results indicate

that: (1) platoons increase the maximum transversal strain values and (2) platoons also decrease in general the positive normalized area under the transversal strain signal. As a result, the platoon configuration reduces the number of cycles to fatigue, for the test conditions present in summer (temperatures between about 25 °C and 27 °C).

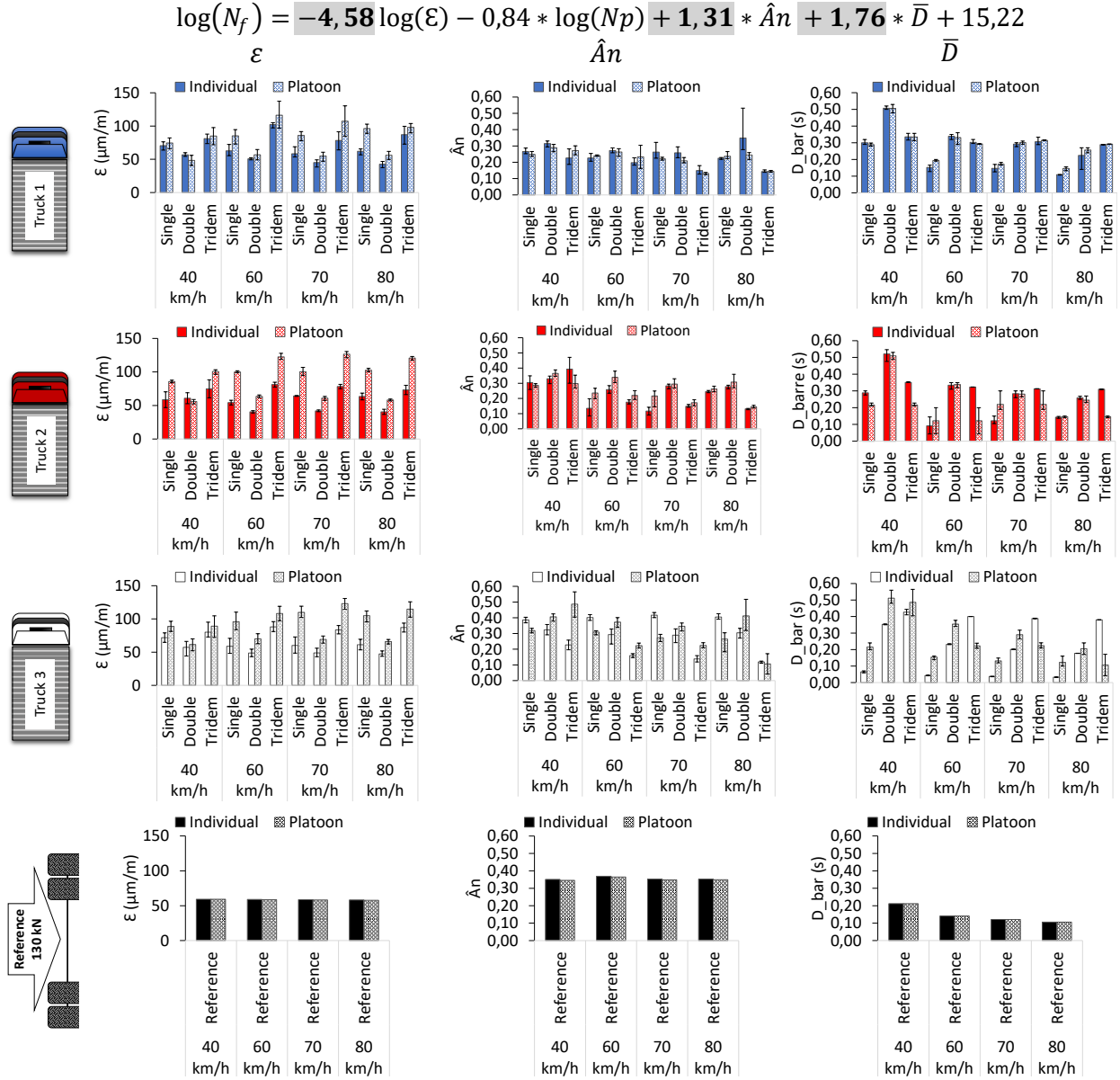


FIGURE 9 Fatigue parameters of the strain signals for the summer campaign (tension is considered positive). Fatigue coefficients obtained from [25]–[27], [30]. **Single:** steer axle, **Double:** driven axle and **Tridem:** trailer tridem axle.

Figure 10 shows the damage ratios of each axle, relatively to the reference 130 kN axle. The highest damage values are obtained for the tridem axles, in the platoon truck configuration. The aggressiveness values of each truck, CA_{truck} are also shown in this figure. It can be seen that:

- In the individual truck configuration, the CA_{truck} values are very similar for all the test speeds, with some variations between trucks, due to the variation in the loads and inter-axle distances between trucks.
- In the platoon configuration, contrary to what was observed in the winter campaign, the CA_{truck} values significantly increase for the three trucks of the platoon, and vary with truck speed. Again, this can be attributed to a more viscoelastic behavior of the asphalt layers at these higher temperatures.
- Additionally, increasing the lateral wander significantly reduces the aggressiveness (CA_{truck} values) of the platoons.

In conclusion, for the warm summer temperatures (here about 27 °C), platooning clearly increases fatigue damage compared with individual trucks. The values are between 28% and 376% higher for a wandering equal to 20 cm at all the test speeds.

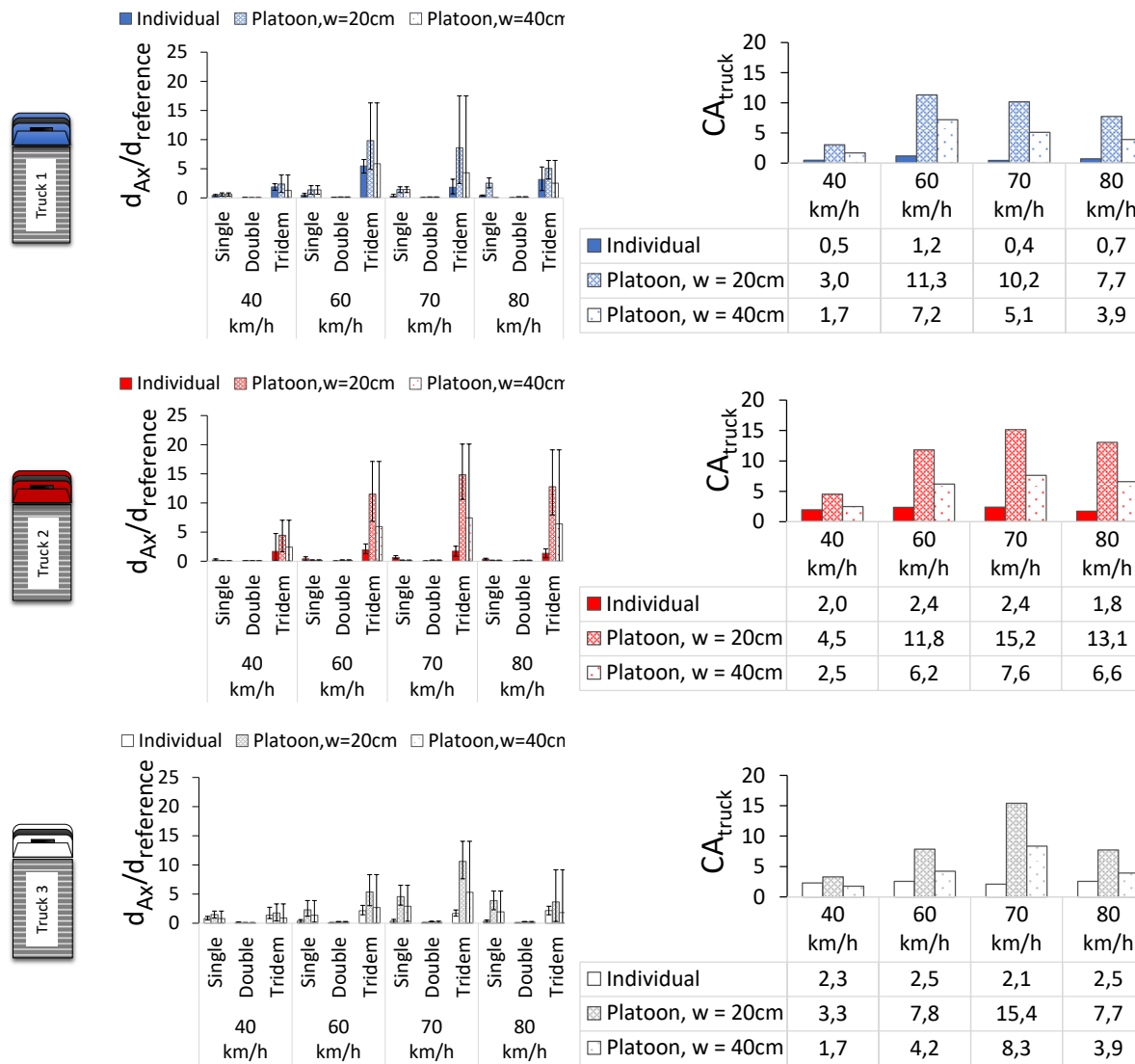


FIGURE 10 Values of fatigue damage per axle and CA_{truck} values for the summer campaign.

3.4. Fatigue life for the different traffic scenarios

Using the CA_{truck} values displayed in the previous sections, it is possible to predict the corresponding number of ESALs by each half-year for the pavement test section under study. The accumulation of this value compared to the number of cycles to fatigue projected by the use of the Homsy fatigue equation, represents the fatigue damage for the structure. In this sense, considering reaching 20% of fatigue damage for each traffic scenario, Figure 11 shows the corresponding remaining fatigue lives expressed in years. In comparison to the reference scenario, which represents the passage of fully loaded 5-axle semi-trailers, in individual configurations, the following trends are observed:

- The first scenario, corresponding to a traffic distribution with 100% of platoons during the winter and no platoons during the summer, does not change the remaining fatigue life of the pavement structure.
- On the contrary, scenarios 2 and 3, corresponding to a traffic distribution with 100% of platoons just during summer or all along the year, significantly decrease the remaining fatigue life, with a maximum reduction of -68% at 70 km/h.
- However, as shown in scenario 4, this effect can be reduced by increasing the lateral wander of the platoons, which is also supported by other results from the literature [4], [17], [18], [20]–[22], [24].

Considering that these measurements were done with fully loaded trucks, and assuming 100% platoon penetration, the negative impact of platoons could be reduced by varying these parameters, as well as by changing the inter-truck distances [17] the truck speeds, and also the time of the day [23] at which platoons are allowed to circulate. It is important to add that the CA values determined in this study are only valid for this pavement structure. Therefore, for different conditions, the corresponding values should be appropriately calibrated.

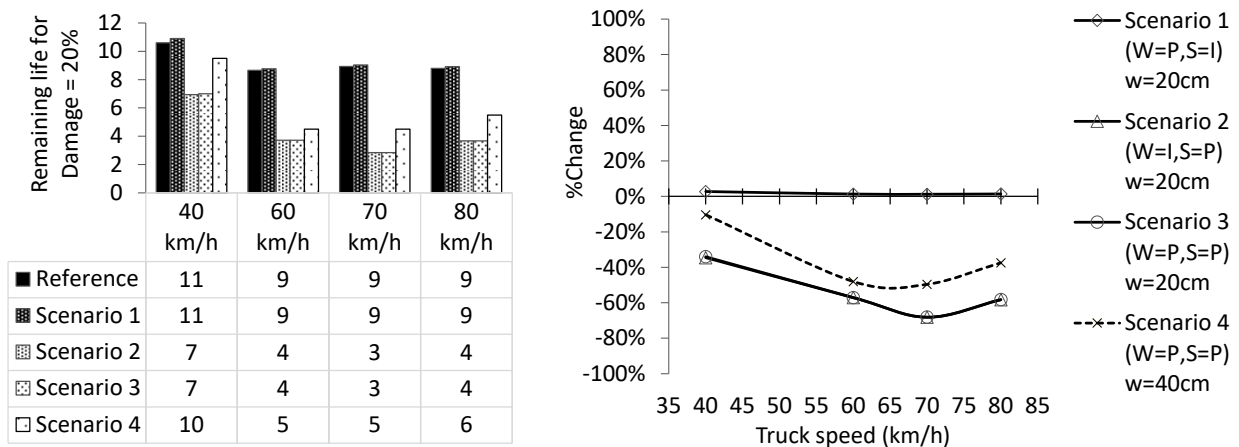


FIGURE 11 Calculated pavement fatigue lives, for 20% of damage, for different platoon traffic scenarios.

3. CONCLUSIONS

This paper presents the results of a study on the effect of platoons on the fatigue life predictions of a European pavement test section. The test protocol and the data treatment proposed in this document are based on an original fatigue model for multiple axle loads, which considers the maximum tensile strain, the number of peaks of the strain signal, the area, and the duration of the strain signal. This approach was applied to strain signals measured by strain gauges installed in an experimental pavement section but can also be used with strain signals obtained by modeling. The following conclusions can be drawn from this study:

- The strain measurements performed on the pavement structure, under 5-axle semi-trailer truck loading, indicated that at the bottom of the asphalt layers, the transversal strains were significantly higher than the longitudinal strains. Strain accumulation effects were also more important for transversal strains, especially at high temperatures (during the summer test campaign).
- With the fatigue model used, which considers the shape of the strain signals, it was clearly shown that for the same loading conditions (same axle loads, speed, and lateral wander), the fatigue damage produced by platoons (compared with single trucks) varies significantly with temperature. At low temperatures (around 10 °C), there was no difference between the damage induced by individual trucks and by platoons. However, at higher temperatures (around 27°C), the damage induced by platoons was significantly higher due to strain accumulation under multiple loads.
- Despite the good predictions obtained with the new fatigue model, further research is carried out, based on laboratory studies, to consider better the most significant effects related to platoon loadings: influence of rest periods and accumulated deformations.
- For the case study presented in this document, truck platoon configurations showed considerably higher fatigue life reductions during summer. In this sense, limiting platooning along this season, or potentially during hours with the highest temperatures, could be a possible management strategy to limit/avoid early pavement fatigue damage. It was also found that the lateral wandering of the trucks has a significant effect and that increasing the lateral wandering could also help limit fatigue damage.
- Following these results, the ENSEMBLE work package related to infrastructure is currently developing further research studies based on parametric studies with a pavement modeling program. The objective is to make a more general analysis of the effects: (1) traffic distribution along the year and along the time of the day, (2) percentage of platoon penetration in the daily and annual traffic, (3) level of loading of the trucks, number of trucks in platoon configuration, (4) lateral wandering, (5) inter-truck distances and (6) representative existing pavement structures. From these simulations, recommendations to limit the impact of platoons will be proposed.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: P. Leiva-Padilla, J. Blanc, F. Hammoum, P. Hornych; data collection: J. Blanc, A. Salgado; analysis and interpretation of results: P. Leiva-Padilla, J. Blanc, F. Hammoum, P. Hornych; draft manuscript preparation: P. Leiva-Padilla. All authors reviewed the results and approved the final version of the manuscript.

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