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The impact of platooning action on asphalt pavement: Monitoring on site

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ABSTRACT: The concept of truck platooning is to take advantage of the connectivity technologies and automated driving support systems to link trucks in close formation (convoy) to increase transport efficiency, reduce fuel consumption and gas emissions while improving road safety. However, closely following guided trucks could have a different impact on road structures than the usual truck traffic. In this context, the study reported in this paper addresses the multi-loading effects of truck platoons on road structures. For this purpose, an experimental test track located in Spain was instrumented with longitudinal and transverse strain gauges. The strain gauges were used to collect the strains obtained in the pavement under the following conditions: (1) trucks in individual and platoon configuration, (2) a time gap of 0.8 s between trucks in the platoon configuration, and (3) four speeds (40 km/h, 60 km/h, 70 km/h and 80 km/h). The viscoelastic response of the pavement structure (strain field) under the test conditions applied on-site was computed using software Viscoroute 2.0 and was compared with the results measured with the strain gauges. Finally, the effect of individual and platoon truck configurations was compared.

Keywords: autonomous truck platoon, pavement performance, full scale test

1 INTRODUCTION

The automotive sector in the last decade has demonstrated the following benefits from partially/fully self-driven truck platooning: (1) better braking/acceleration abilities of the vehicles, (2) reduction of fuel consumption and operating costs of the vehicles, (3) enhancement of road safety for less traffic accidents and better traffic control, among others (Gungor & Al-Qadi, 2020; Hoque et al., 2021; Konstantinopoulou et al., 2019; Ladino et al., 2021; Thunberg et al., 2019).

Despite all the already mentioned benefits, a truck platoon deployment without precaution can accelerate pavement damage due to (Chen et al., 2019; Gungor & Al-Qadi, 2020; Noorvand et al., 2017): (1) the channelization of truck loading, which reduces the scattering in the lateral position of human-driven trucks, and (2) the reduction in the inter-truck distances, which may hinder the self-healing capacity of asphalt concrete materials.

In this context, since 2018, the European Union has been developing the research project called ENSEMBLE, which main objective is to pave the way for the adoption of multi-brand truck platooning in Europe, to improve fuel economy, traffic safety, and throughput (Ladino et al., 2021; Mascalchi et al., 2020).

This paper presents part of the research efforts done by ENSEMBLE to evaluate the effect of platooning trucks on pavement structures. For this purpose, a test section of a full-scale pavement was instrumented and subjected to the passage of trucks in individual and platoon configurations. The experimental results were simulated with a viscoelastic model, using the software Viscoroute 2.0 (Chabot et al., 2010).

2 MATERIALS AND METHODS

2.1 Pavement structure and instrumentation

The test section corresponding to this research is located in the test track facilities of the automotive company IDIADA Applus in Tarragona, Spain. As shown in Figure 1, the pavement structure of the test section is composed of a zahorra foundation (Spanish term for a granular material with continuous grading) and three asphalt layers in the top: 15 cm of a subbase layer, 6 cm of a base layer and 4 cm of a wearing layer. According to the UNE-EN 13108-1 asphalt mixture classification, the types of asphalt mixtures are respectively: AC 22 G (G-20), AC 22 S (S-20), and AC11 surf (D12). 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 Figure 1 shows, the instrumentation installed to measure the fatigue performance of the test section consists of an array of 24 strain gauges. Half of the strain gauges were used to measure the transverse strains (12 strain gauges) and the remaining half the longitudinal strains (12 strain gauges) at both the bottom of the base layer (six strain gauges) and the bottom of the subbase layer (six strain gauges). The strain gauges were installed under the right path of the truck, with a spacing of 20 cm in the transversal direction. Thermocouples were also installed at the bottom of each asphalt layer at two different locations, with a total of six thermocouples used to monitor the pavement temperature at different pavement depths during testing.

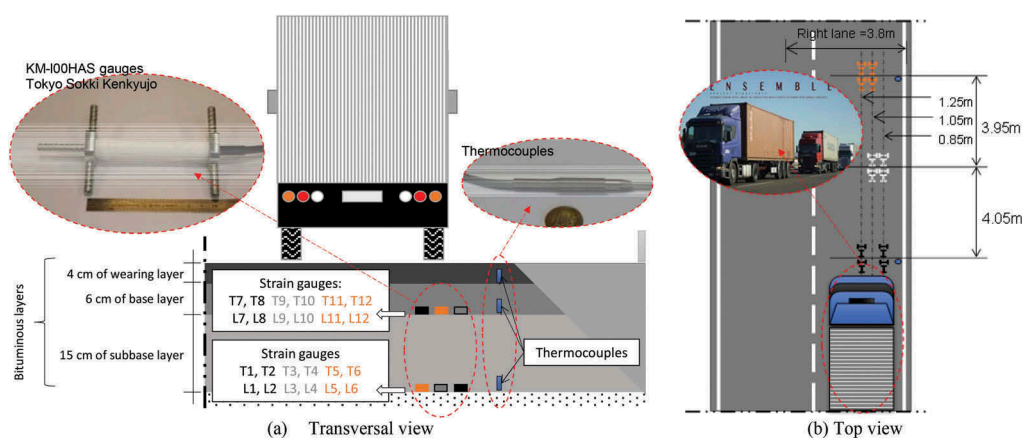


Figure 1. Pavement structure and instrumentation (the images are not to scale).

2.2 Test protocol

To evaluate the platooning effect of semi-autonomous/autonomous trucks, the test protocol defined in this experiment was based on using 3 semitrailer trucks (5-axle), with the loads and geometry shown in Figure 2. To simulate more easily different positions and speeds, the trucks were driven by human drivers. The platooning configuration defined for the test considered the following characteristics: (1) trucks in individual and platoon configuration with three trucks; (2) 0.8 s time gap for inter-truck separation; (3) lateral deviation of Axle 1 to each strain gauge is approximately zero (i.e. wandering \cong 0 cm, measured by using a laser installed in the guard line and a reflective disc placed in the right wheel of the steer axle of each truck); (4) variation of temperature conditions through two test campaigns, one carried out in winter and the other one in summer; (5) four different test speeds, 40 km/h, 60 km/h, 70 km/h and 80 km/h.

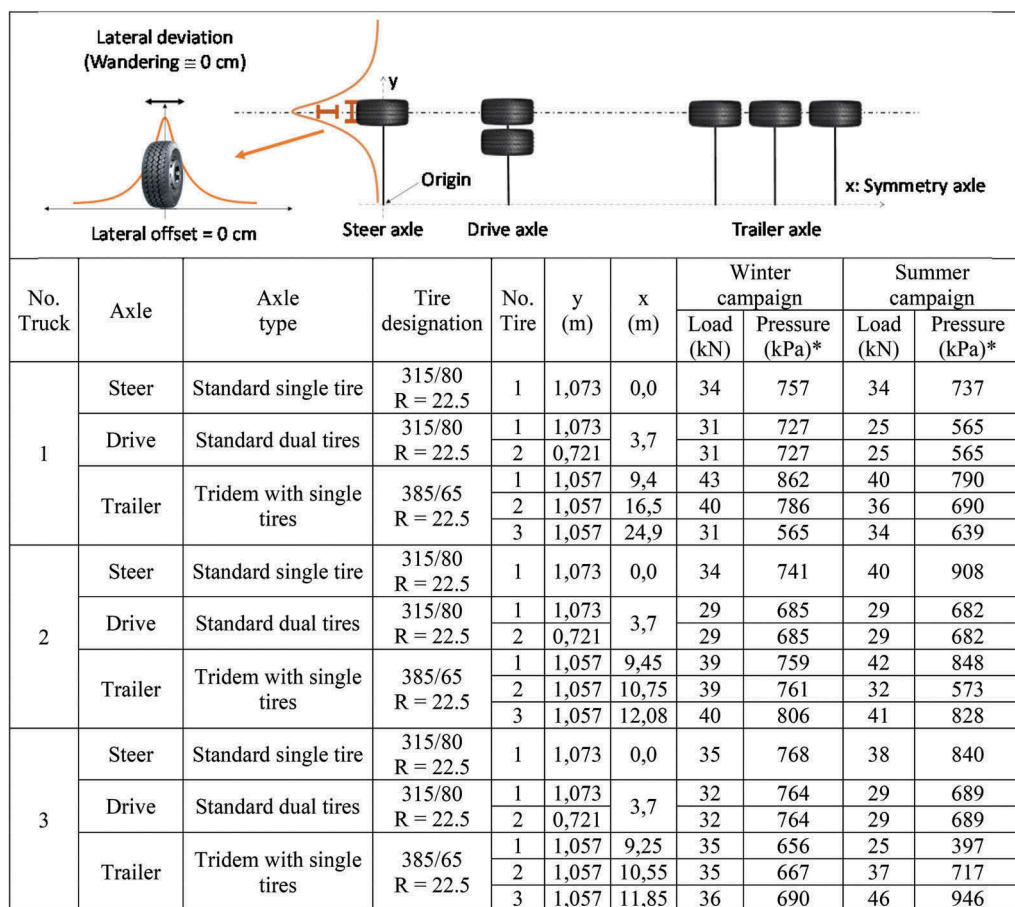


Figure 2. Loads and geometries corresponding to the right axles of each truck.

Note Figure 2: * Pressure values estimated from (Bridgestone, 2020; European Commission Directorate General Transport, 2001).

2.3 Pavement modeling

2.3.1 Material properties and geometry

As shown in Table 1, the pavement structure used in the model is composed of seven layers, considering a foundation layer and three asphalt layers, with three thin interlayers at the interfaces. Table 1 shows each layer thickness, Poisson ratio, modulus, and material behavior, as well as the corresponding pavement temperature used for each test campaign and load configuration. The modeling was done using the software Viscoroute 2.0 (Chabot et al., 2010). It is a semi-analytical software, developed to model pavement response under moving wheel loads, considering elastic or visco-elastic pavement materials. The viscoelastic behavior of the asphalt layers was simulated using the Huet-Sayegh model, which equation and parameters are shown in Table 2.

Table 1. Material properties used in the model.

Layer	Thickness (m)	Poisson ratio	Modulus (MPa)	Material behavior	Pavement temperature (°C)			

					Winter		Summer	
					Indiv.	Plat.	Indiv.	Plat.
Wearing course	0.040	0.35	Master curve *	Viscoelastic	12.8	4.5	24.9	34.1
Thin interlayer	0.002				12.8	4.5	24.9	34.1
Base layer	0.060				11.3	6.1	25.9	27.0
Thin interlayer	0.002				11.3	6.1	25.9	27.0
Subbase layer	0.150				10.3	8.3	27.5	27.7
Thin interlayer	0.002	0.40	180 **	Elastic	10.3	8.3	27.5	27.7
Foundation	-				-	-	-	-

Notes Table 1:

*Tack coat, typical values for a bitumen emulsion: Huet-Sayegh parameters (Table 2).

**Common value for a zahorra (Spanish nomitation for a granular material with discontinuous grading) and a heavy traffic, NTL-357/98.

***Temperature values measured with the temperature probes installed on the test section.

Table 2. Huet-Sayegh parameters at 15°C for viscoelastic characterization of the asphalt layers.

Huet Sayegh*:	$E^*(\omega, \tau) = E_0 + \frac{E_\infty - E_0}{1 + \delta(i\omega\tau(\theta))^{-k} + (i\omega\tau(\theta))^{-h}}$									
Adjustment factor*:	$\tau(\theta) = \exp(A_0 + A_1\theta + A_2\theta^2)$									
Layer	Material type	E_∞ (MPa)	E_0 (MPa)	δ	k	h	A_0	A_1	A_2	
Wearing	AC11 surf (D12) **	19644	19	2,535	0,213	0,628	3,072	-0,382	0,002	
Base	AC22 S (S-20) ***	27320	511	5,387	0,194	0,556	8,395	-0,389	0,001	
Subbase	AC22 G (G-20) ***	22114	328	6,400	0,190	0,566	9,058	-0,387	0,001	
Interlayer	Tack coat ****	1968	0	9,048	0,272	0,883	-1,629	-0,391	0,002	

Notes Table 2:

* E_∞ : instantaneous modulus, E_0 : long term modulus, k and h : parabolic elements ($1 > h > k > 0$), δ : dimensionless coefficient managing the contribution of the first spring to the overall behavior of the bituminous material, ω : loading time (frequency), $\tau(\theta)$: adjustment factor, θ : test temperature, A_0 , A_1 , A_2 : adjustment factors.

**Very thin asphalt concrete (VTAC) layer (Duong et al., 2018).

***Calculated with data obtained from the study (Mateos & Soares, 2015).

****Typical values obtained for a bitumen emulsion (Duong et al., 2018).

2.3.2 Boundary conditions

As Figure 3 shows, the load contact area used for modeling is composed of five rectangles distributed along the traffic line according to each axle position. The five rectangles represent the right half of the five axles that compose the semitrailer trucks used during testing. Each rectangle geometry was determined by fixing the width to 25.5 cm and 28.3 cm depending on the type of tires used, 315/80 R = 22.5 and 385/65 R = 22.5 respectively, as well as the tire loads and pressures already shown in Figure 2.

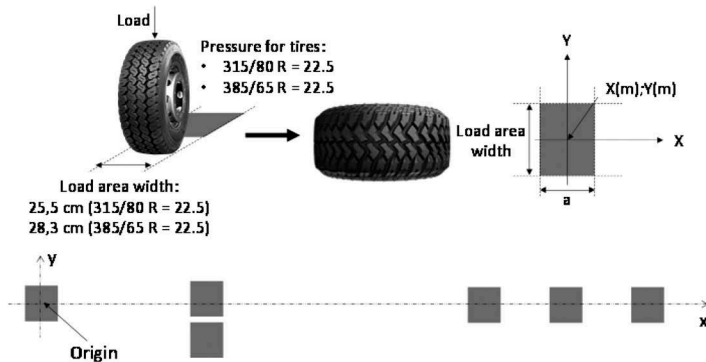


Figure 3. Load areas used during modeling (the images are not to scale).

3 DISCUSSION OF RESULTS

3.1 Transverse strains

The transverse strain signals obtained at the bottom of the subbase layer were selected in this paper, to evaluate bottom-up fatigue cracking of the asphalt layers. Figure 4 and Figure 5 show a comparison between the values measured with the transverse strain gauges installed in the test section, for truck speeds of 40 km/h and 80 km/h, during the winter and summer campaigns respectively, and obtained by the modeling process with Viscoroute 2.0. Figure 6 shows the inter-truck distances correspondingly applied for each speed tested. Truck passages with zero-wandering values for each truck in both individual and platoon truck configurations were selected for the analysis. The following observations can be made on these transverse strain signals:

- The transverse strain signals predicted with Viscoroute 2.0 are in good agreement with the real measured signals.
- The transverse strain values present a slow return to zero after loading, indicating a delayed strain response (and possibly some permanent deformations) in the material. This strain accumulation is more important for the summer campaign and for the platoon configuration (Figure 5). In terms of modeling, three interface configurations were probed to analyze the way to simulate this delayed response: (a) fully bonded layers, (b) sliding layers and (3) viscoelastic thin interlayer. From the results obtained, it was found that to reproduce the sliding effect occurring at the interfaces, thin viscoelastic tack coat interlayers should be included (Duong et al., 2018).
- The transverse strain values obtained under the passage of the trucks are only in tension. Once the vehicle passes, the values tend to return to the original condition with a delay caused by the viscoelastic performance of the material in the asphalt layers.
- In general terms, the strain values obtained in summer, with pavement temperatures ranging from 25.0°C to 29.5°C, are much higher (1.32 to 3.50 times and 1.62 to 4.93 times in the individual and platoon configuration respectively) than the strains measured in the winter, when the temperatures range from 6.1°C to 11.3°C.

- For the winter campaign, truck platoon configurations seem to have a negligible effect on the maximum transverse strain values obtained compared to the ones obtained in individual configurations. In contrast, for the summer campaign, the values obtained under platoon truck configurations are 0.76 to 2.0 times higher (depending on the speed, the type of axle and the truck) than individual ones.
- Using a constant time gap to represent platoon truck configurations based on vehicle reaction times means an increase in the inter-truck distances when truck speeds increase.

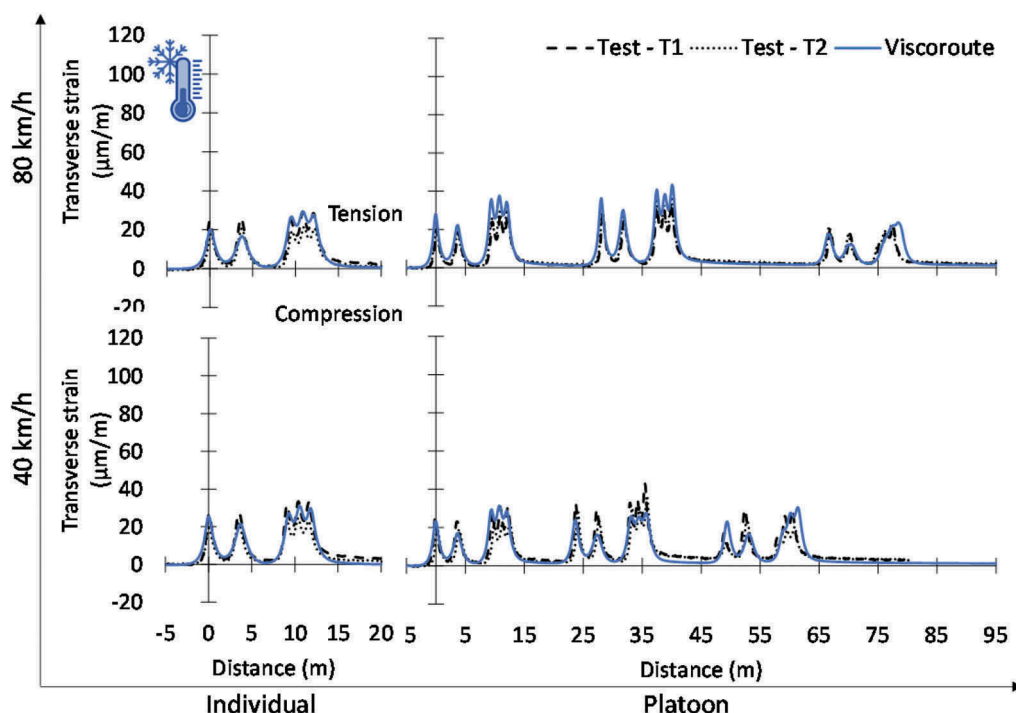


Figure 4. Measured and calculated transverse strains at the bottom of the subbase asphalt layer (winter campaign).

3.2 Longitudinal strains

Considering the longitudinal strain gauges at the bottom of the subbase layers, Figure 7 and Figure 8 show the comparison between the values measured and the values obtained by modeling for truck speeds of 40 km/h and 80 km/h. In addition, Figure 9 shows a comparison between the maximum longitudinal and transversal values obtained under the passage of each axle. In this case, the following observations can be made:

- Like transverse strain signals, the longitudinal strain signals predicted with Viscoroute 2.0 follow closely the real measured longitudinal strain signals.
- For all the cases, the shape of the longitudinal strain signals is significantly different from the shape of the transverse strain signals. The longitudinal signals are first in compression (when the load approaches) then in tension (under the center of the load), and finally in compression again after loading.
- Similar to the transverse strains, the longitudinal strains are much higher (ranging from 1.58 to 2.58 times higher in the individual configuration and from 1.90 to 4.86 times higher in the platoon configuration) in the summer, when the measured pavement temperatures

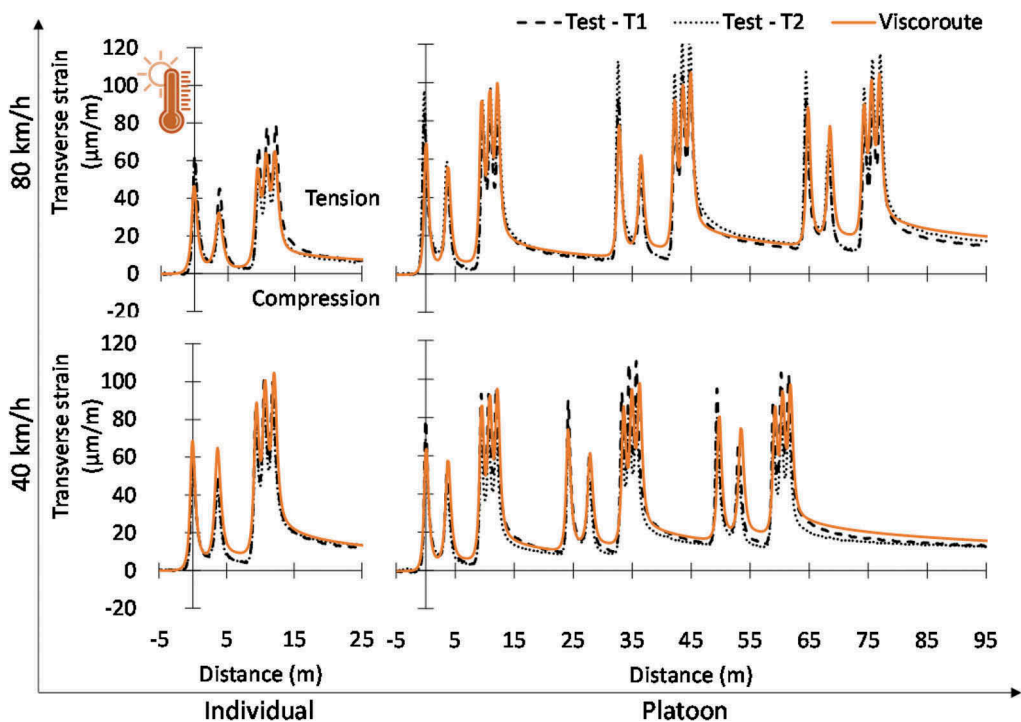


Figure 5. Measured and calculated transverse strains at the bottom of the subbase asphalt layer (summer campaign).

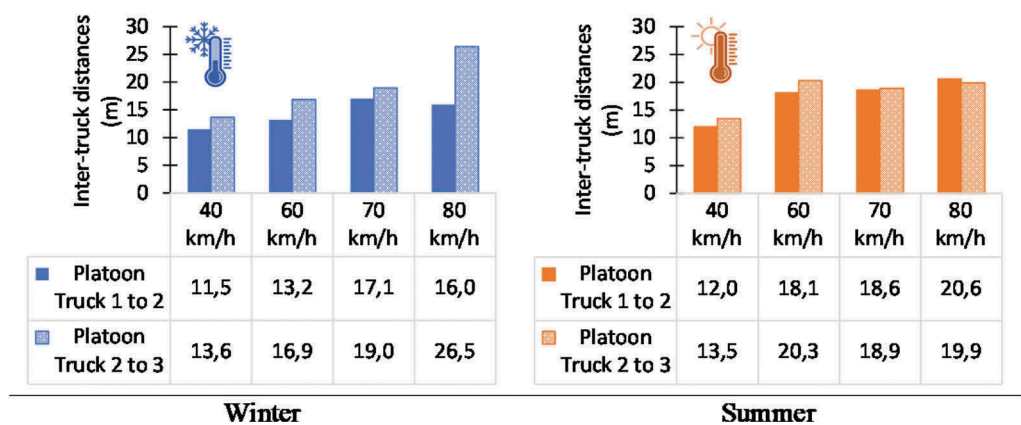


Figure 6. Inter-truck distances in the platoon configuration.

range from 25.0°C to 29.5°C, in comparison to the ones obtained in the winter, when the temperatures range from 6.1°C to 11.3°C.

- Like the transverse strains, truck platoon configurations seem to have a negligible effect on the maximum longitudinal strain values obtained for the winter campaign. In contrast, the values obtained under platoon truck configurations for the summer campaign are 0.65 to 1.27 times higher than individual ones.

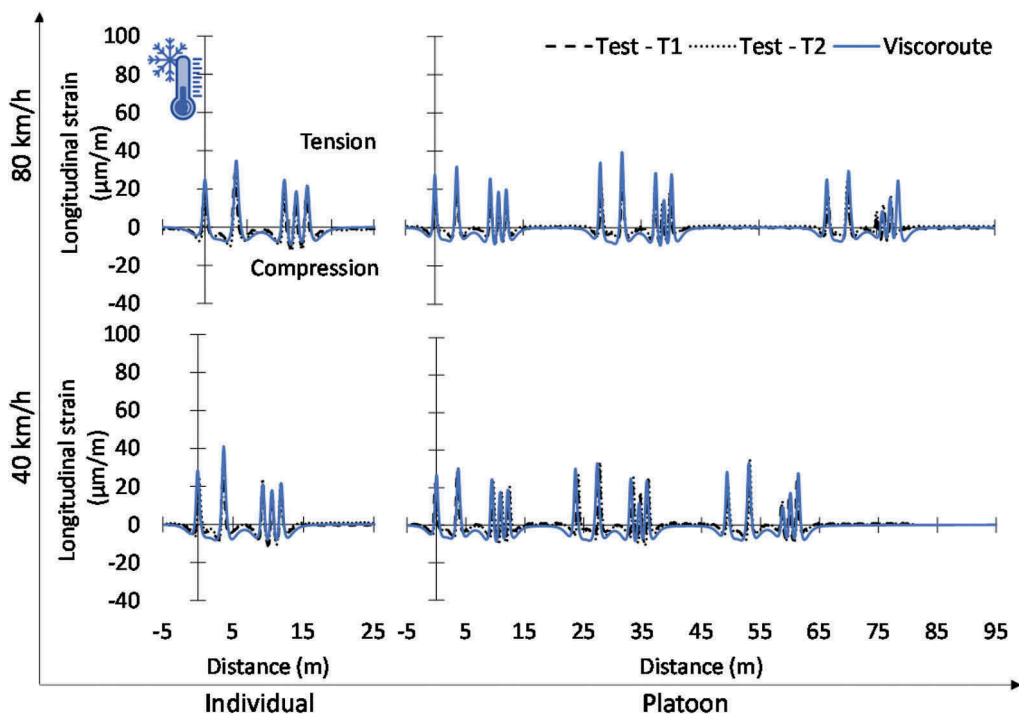


Figure 7. Measured and calculated longitudinal strains at the bottom of the subbase asphalt layer (winter campaign).

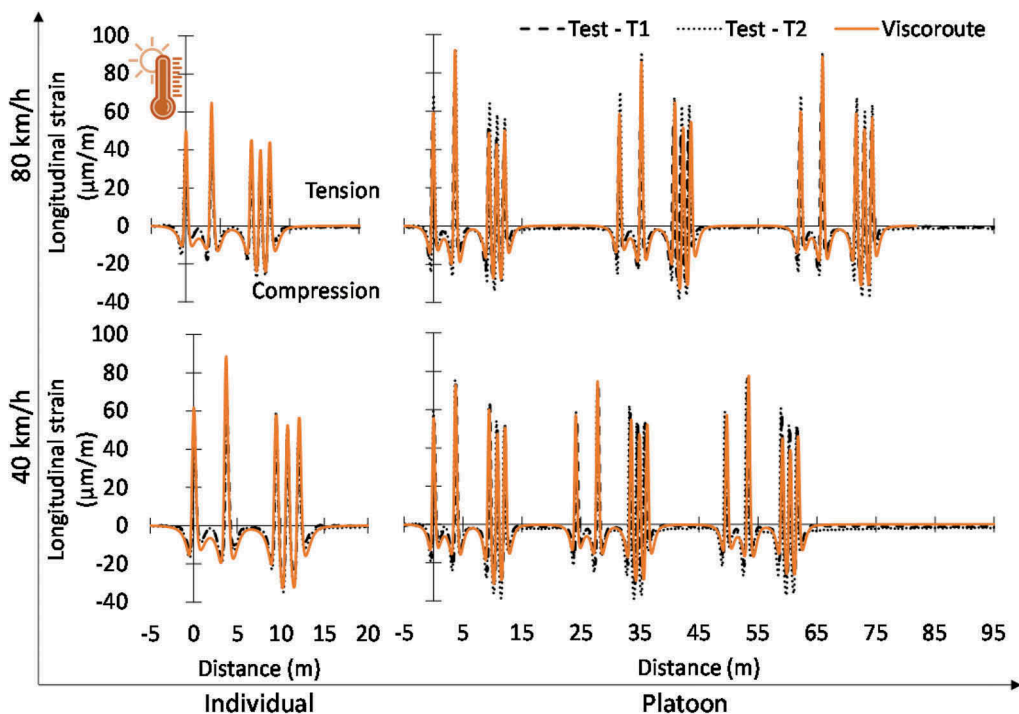


Figure 8. Measured and calculated longitudinal strains at the bottom of the subbase asphalt layer (summer campaign).

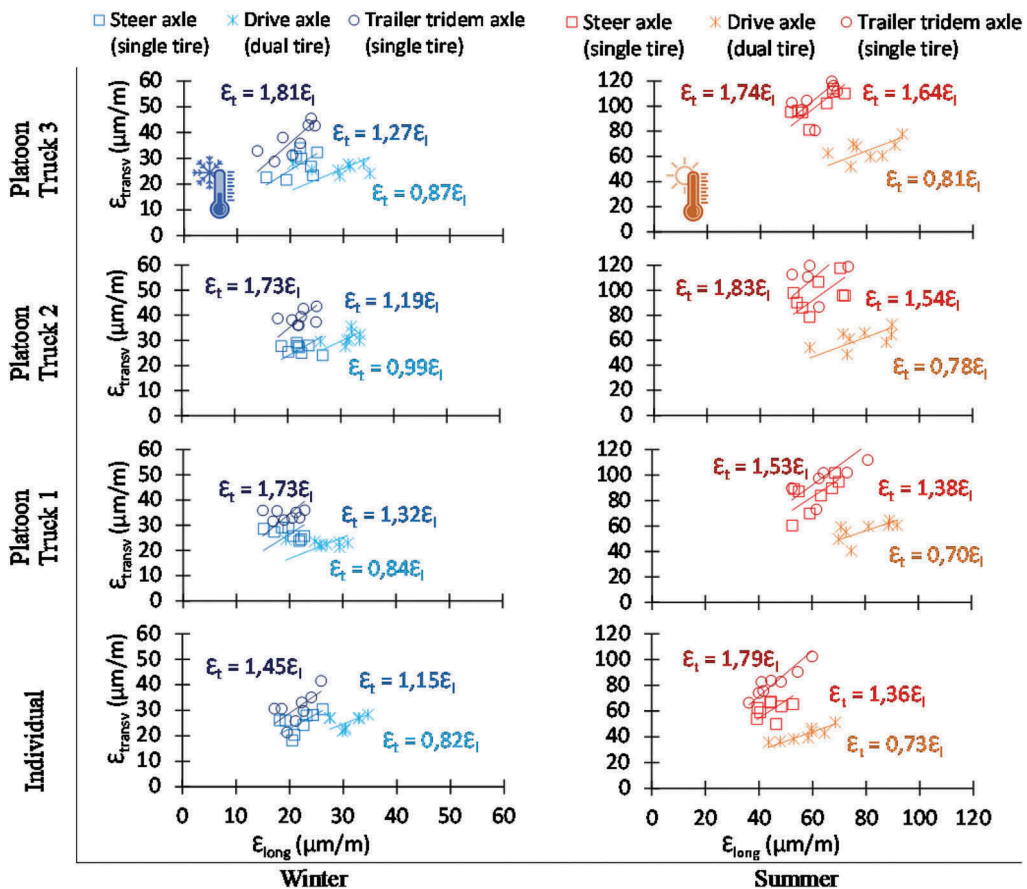


Figure 9. Comparison of the maximum transverse/longitudinal strains.

- For the conditions tested, individual/platoon truck configurations, and winter/summer test campaigns, by the analysis of the slopes of the linear equations relating longitudinal and transverse strains (Figure 9), the maximum strain values obtained are higher in the transversal direction for the single wheel axles (steer and trailer), the highest values being obtained for the trailer (from 1.45 to 1.83 times higher). In this sense, it can be expected that fatigue cracking will develop in the longitudinal direction along the vehicle's passage.

4 CONCLUSIONS

This paper presents some of the results obtained from a full-scale test performed on a pavement test section subjected to individual and platoon truck loadings. Three non-autonomous semi-trailer trucks were driven by different drivers to configured platoon truck configurations with 0.8 s time gaps and testing speeds of 40 km/h, 60 km/h, 70 km/h and 80 km/h, during two test campaigns, carried out in winter and summer conditions. The viscoelastic responses of the pavement structure (strain fields) were modelled using the software Viscoroute 2.0, for different speed and temperature conditions, and compared with the experimental measurements.

The study has led to the following conclusions: (1) the model with viscoelastic interfaces was able to reproduce correctly the experimental strain values; this confirms the capacity of Viscoroute to predict pavement response under complex multiple load

conditions, and the possibility to use it as a predictive tool to evaluate the effect of other platoon configurations; (2) both transversal and longitudinal strains were considerably higher for the higher temperatures of summer, due to the thermoviscoelastic behavior of the asphalt layers; (3) the highest level of strains were obtained for the trailer tridem axle and the transversal direction, in the summer campaign; (4) transverse strains also showed important strain accumulation after the passage of the vehicles, especially in the platoon configuration; (5) only for the case of the summer campaign, platoon truck configurations showed higher maximum transversal/longitudinal values than the individual truck configurations. These results suggest that pavement fatigue damage induced by platooning could be mitigated by controlling parameters like traffic times (to avoid hot temperatures), inter-vehicle distances and lateral wandering.

As a continuation of the experimental measurements presented in this paper, it is planned, in the ENSEMBLE project, to perform laboratory fatigue tests, reproducing the same multiple axle strain signals, to study the influence of multiple axles, and platoon configurations, on the fatigue performance of the bituminous layers. Additionally, recognising that platooning trucks can also have important impacts in terms of rutting, especially at reduced wandering patterns, further research studies will also be oriented to investigate the effect of platoons on vertical strains and therefore permanent deformation of asphalt pavements.

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