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The Impact of Truck Platooning Action on Asphalt Pavement: A parametric study

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The Impact of Platooning Action on Asphalt Pavement: A parametric study

Partially/fully self-driven trucks in platoon configurations promise to increase transport efficiency, reduce fuel consumption/gas emissions and improve road safety through the use of connectivity technologies and automated driving support systems. However, truck platooning means the introduction of new types of loads on pavements which are characterised by: multiple loads, generated by the multi-axle configurations of the different trucks forming the platoon, traffic channelization by the reduction of the lateral deviation of the trucks, and reduced inter-truck time gaps, which may reduce the self-recovery capacity of asphalt concrete materials, reducing the pavement service life. In this context, this study presents a parametric analysis carried out to evaluate a pavement structure subjected to several platoon truck configurations. The results of the study indicated that to keep the same pavement structural response as for individual trucks, it is possible to act on the following parameters in the platoon configuration: traffic distribution along the year and along the time of the day (avoiding traffic at higher temperatures), percentage of platoon penetration in the daily and annual traffic, level of loading of the trucks, number of trucks in platoon configuration, wandering, and inter-truck time-gaps/distances.

Keywords: truck platooning; autonomous trucks; pavement performance; wandering; multi-axle loads; reduced rest periods.

Introduction

In the last few decades, the automotive industry has made an important effort on using Connectivity Vehicle Technologies (CVT) and Automated Driving Support Systems (ADAS) to develop partial/full automation of vehicles (AV) (Chen et al. 2020, Song et al. 2021, Zhu & Ukkusuri 2018). The AV promises to reduce risks and costs associated with accidents, travel time and pollution, to maximise fuel savings and energy efficiency (Chandra & Nguyen 2020, Chen et al. 2019, Taylor et al. 2020, Vahidi & Sciarretta 2018). However, despite the already mentioned benefits, this new way of operating vehicles modifies the traffic loads applied to pavements and, therefore, their

remaining service life. In the case of trucks in platoon configurations, these new types of loads are characterised by:

- (1) multiple loads, generated by the multi-axle configurations of the group of trucks forming the platoon,
- (2) traffic channelization, by the reduction of the lateral deviation of the trucks (Chen et al. 2019, 2020, Gungor et al. 2020, Gungor & Al-Qadi 2020b, 2020a, Marsac et al. 2020, Noorvand et al. 2017, Rana & Hossain 2021, Song et al. 2021, Zhou et al. 2019), and
- (3) reduced inter-truck time gaps (Gungor et al. 2020, Gungor & Al-Qadi 2020b, 2020a), which may reduce the self-recovery capacity of asphalt concrete materials, reducing the pavement service life.

According to a recent study (Noorvand et al. 2017) based on mechanistic-empirical analysis of pavements using the AASHTOWare Pavement ME Design for the United States, in terms of rutting and fatigue damage, the pass of an autonomous truck in uniform wandering distribution (same number of vehicles passing along the all wandering interval) is equivalent to 0.65 and 0.81 passes of a non-autonomous truck. A similar study based on finite element modelling (Chen et al. 2019, 2020, Song et al. 2021) indicates that in terms of rutting, the pavement maintenance intervals could be extended by 2.3 years (in reference to the scenario without wandering) by controlling the lateral distribution of autonomous trucks. The same study also found that for flexible pavements, fatigue damage can be reduced by up to 35% under repeated standard axle loads, by implementing the same lateral distribution control strategy.

A similar study using the software Wander 2D, which uses statistics and applied mathematics to improve the MEPDG inputs relative to wandering, demonstrate that in comparison to the channelized traffic condition, the pavement life-cycle costs can be

reduced by controlling the platoon lateral position (Gungor et al. 2020, Gungor & Al-Qadi 2020a).

Other studies (Rana & Hossain 2021), also based on mechanistic-empirical analysis of pavements, found that increasing the wander uniformly and assigning mainly the traffic to low-temperature periods of the day can reduce pavement distress projections due to fatigue and rutting.

Since road pavements are valuable assets for a nation and their construction and maintenance are expensive and generate environmental impacts, careful deployment of partial/full autonomous trucks in platoon is vital, to contribute to cleaner and more durable road infrastructures (Bajwa et al. 2017, Chen et al. 2020).

In this context, the European Commission is supporting since 2018 a 3-year H2020 research project called ENSEMBLE. As stated by its acronym, ENSEMBLE has been oriented to “ENabling Safe Multi-Brand Platooning for Europe”. This project is led by the Dutch Organisation for Applied Scientific Research (Dutch acronym: TNO) and associates six European truck manufacturers (DAF, DAIMLER, IVECO, MAN, SCANIA and VOLVO Group), the European Association of Automotive Suppliers (CLEPA), equipment manufacturers (NXP, ZF, Bosch, Continental, Brembo), ERTICO-ITS Europe (link with the European Truck Platooning Community), and knowledge partners (IDIADA Applus, Gustave Eiffel University, Royal Institute of Technology and VU Brussel).

As a partner of the project, Gustave Eiffel University (previously known by the French acronym IFSTTAR: French Institute of Science and Technology for Transport, Development and Networks) has carried out various studies (Leiva-Padilla et al. 2022, Leiva-Padilla et al. 2022, Marsac et al. 2020) focused on the evaluation of the effect of platooning trucks on pavements.

The first study (Marsac et al. 2020) was based on developing a numerical model using the ViscoRoute© 2.0 software, which can simulate viscoelastic pavement response under dynamic loading. According to the study's findings, increasing the lateral deviation of the trucks by 25 cm can reduce the maximum strain values by 12%, and consequently fatigue damage by a ratio of 6, in comparison to loading with no lateral wheel wander.

The second and third studies (Leiva-Padilla et al. 2022; Leiva-Padilla et al. 2022) are based on an experimental campaign, carried out on the Applus IDIADA test tracks, which objective was to monitor the response of a bituminous pavement test section, submitted to platoon truck configurations. Two test campaigns were performed in winter and summer, with variable test conditions: individual and platoon truck configurations, four test speeds: 40, 60, 70 and 80 km/h, two intervals of lateral wandering: ± 10 and ± 20 cm, fully loaded trucks: 40 to 44 tons). The results of these tests indicated that:

- (1) transverse strains were higher than longitudinal ones for the type of trucks used during testing (T3S2, representative for Europe).
- (2) There is a strain accumulation effect under multiple truck loading, mainly noticed at high temperatures, which can lead to increased pavement damage, under platoon configurations.
- (3) Contrary to what is observed in the summer, at high temperatures, the impact of platooning trucks is practically negligible in the winter, at low temperatures.
- (4) Increasing the interval of lateral deviation (wander) can reduce the effect of platooning trucks in the summer.

In this context, following the same line as in the three previously described studies, this document presents the results of a parametric study performed after the

validation of a numerical model, used to predict strain values obtained in the experimental campaign described in the study done by Leiva-Padilla et al. (2022). The numerical model is based on the ViscoRoute© 2.0 software (Chabot et al. 2010). ViscoRoute is a semi-analytical pavement modelling software, which can consider elastic and visco-elastic materials, described using the Huet-Sayegh model (Huet 1965, Sayegh 1966). In this study, attention is also paid to the modelling of asphalt layer interfaces and different hypotheses are used to describe their behaviour: perfectly bonded, sliding, and interfaces described by thin viscoelastic layers.

The parametric study consisted in varying the following parameters associated with truck platoon configurations: inter-truck time gaps, number of trucks in the platoon, lateral deviation of each truck in the platoon (wandering), level of loading of the trucks, truck speeds and pavement temperatures. Based on the results, solutions for reducing the impact of platoons on pavement damage are discussed.

Materials and methods

The test section used for the model validation of this study is located in the test track facilities for automotive applications of the company Applus IDIADA in Tarragona, Spain. This test section has a pavement structure characterized by a subbase consisting of unbound granular materials with continuous grading and 3 asphalt layers.

In summary, according to EN 13108-1:2016, the asphalt layers are composed by mixtures type AC 22 G (G-20), AC 22 S (S-20), and AC 11 surf (D12), where the AC stands for “Asphalt Concrete” while the number is the nominal maximum aggregate size in mm, G and S: coarse and semi-dense granulometry). Strain gauges in the transverse and longitudinal direction and thermocouples were placed at the bottom of the binder course and base course. The details about the materials, type of instrumentation placed and test protocol followed during the experimental part of this

project can be consulted in previous research studies and technical reports (Leiva-Padilla, Blanc, Salgado, et al., 2022; Leiva-Padilla, Blanc, Trichet, et al., 2022; Leiva-Padilla, Schmidt, Blanc, et al., 2022).

For the purpose of this study, the following situations were considered: Trucks in individual/platoon configurations, inter-truck distance equivalent to a reaction time gap of 0.8 s, close to zero lateral deviation of the trucks, summer test campaign at 40 km/h (critical conditions for truck platooning).

Numerical simulation

Step 1: Model validation

The first objective of the numerical simulation was to validate a model, capable of predicting the mechanical response of the test section, and the different test conditions described previously. The Viscoroute software was used for the calculations, and 3 different hypotheses were successively tested:

- Model 1 - Fully bonded interfaces.
- Model 2 - Sliding interfaces (no friction).
- Model 3 - Viscoelastic interfaces represented by thin interlayers, 2 mm thick, consisting of bituminous emulsion (see Table 1). In this case, the viscoelastic interlayers were defined in Viscoroute as additional layers with their corresponding viscoelastic properties. This means that, Viscoroute uses the same principles than for asphalt layers but with the thickness and viscoelastic properties of an emulsion.

The Huet-Sayegh (Chailleux et al. 2006) parameters used to describe the viscoelastic performance of the asphalt layers were calibrated using the data obtained for a range of Spanish mixtures (Mateos & Soares 2015) similar to those used for the

test section of this study. These parameters were calculated using the Viscoanalyse Web Application (Challieux, 2021) specially designed to assist the interpretation of material complex modulus.

Table 1. Huet-Sayegh parameters at 15°C for characterisation of 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
Binder course	AC22 S (S-20) ***	27320	511	5.387	0.194	0.556	8.395	-0.389	0.001
Base course	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 controlling the contribution of the first spring to the overall behaviour of the bituminous material, ω : angular frequency, $\tau(\theta)$: adjustment factor, θ : test temperature, A_0, A_1, A_2 : adjustment factors.

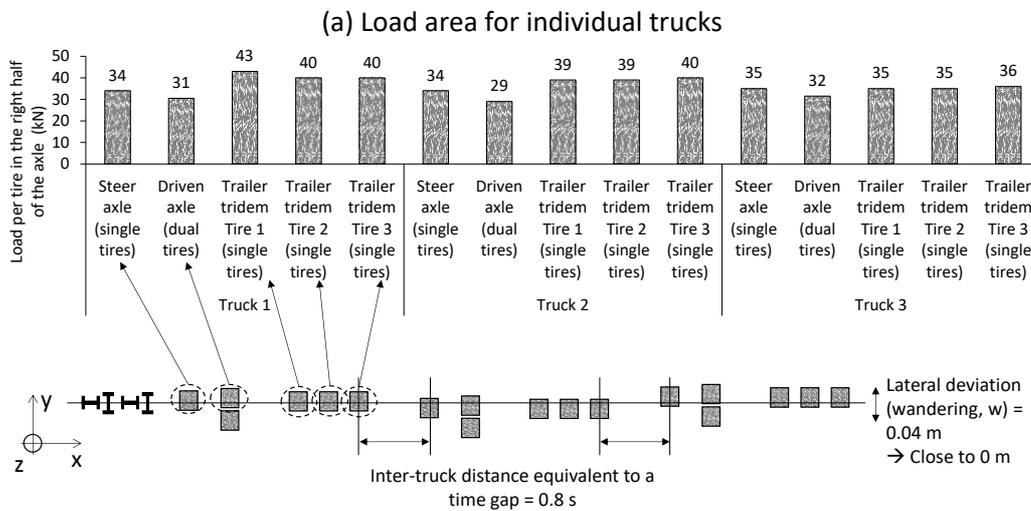
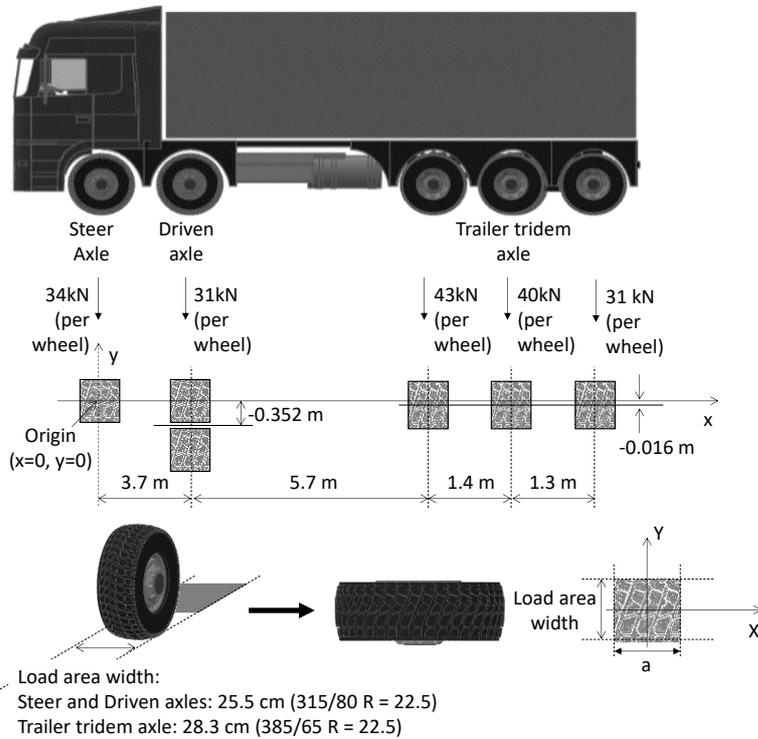
**Very thin asphalt concrete (VTAC) layer (Duong et al., 2018).

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

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

As shown in Fig. 1a, the loads considered in the calculations correspond to the right-half axle of each truck in the platoon. The loads of each truck are described by six rectangular areas, loaded by a uniform vertical pressure, which in comparison to circular, elliptical and square areas, showed the closest values to the ones obtained by testing. The rectangular areas for the steer and driven axle were 25.5 cm wide (tire type: 315/80 R = 22.5) and for the trailer tridem axle 28.3 cm wide (tire type: 385/65 R = 22.5). The length for all the cases varied according to the type of tire used, and the load applied on it. Fig. 1b shows the loads corresponding to each tire, for the complete truck platoon configuration (18 rectangles, 6 per truck). This geometry corresponds to the passage selected for modelling, where the lateral deviation of each truck in reference to

the strain gauges is approximately zero for each truck traveling at 40 km/h and during the summer test campaign.



(b) Load area for trucks in platoon configuration

Fig. 1. Semitrailer truck areas used in the model validation.

Note Figure 1: Tire pressure values were estimated from (Bridgestone 2020, European Commission Directorate General Transport 2001), according to the applied loads.

Fig. 2 compares the strain values measured with 2 transverse and 2 longitudinal strain gauges (dashed black lines) placed at the bottom of the asphalt base course with

the values predicted by the three models, with fully bonded, sliding and viscoelastic interfaces. The results show that only the model with viscoelastic interlayers predicts correctly the delayed strain recovery and consequent strain accumulation produced by the passage of multiple axle loads. This strain accumulation effect is more important for transverse strains than for longitudinal strains. Therefore, this model, giving the best results, has been selected for the parametric study.

To evaluate the quality of the model prediction, the sum of the maximum strain values measured under the passage of each axle of truck 3 has been compared with the calculated strains. For the model with viscoelastic interlayers, the errors (sum of the maximum strain values obtained for each axle of truck 3 for both testing and modelling, both in the transverse and the longitudinal direction) are respectively 5% and 3% for the transverse and longitudinal strains. The sum of the maximum strain values was used after observation of the importance of the strain accumulation produced during testing by platoons at high temperatures and mainly in the transverse direction. Only the results obtained for the transverse strains (which present higher values than the longitudinal strains) will be analysed in the following sections.

Here it is important to remark the usefulness of numerical modelling to reduce the costs and the time associated with long and extensive testing campaigns. A proper validation of this model worked as a solid base in this study for the posterior parametric study of platoons.

- - -Test - T1 Test - T2 — Viscoroute

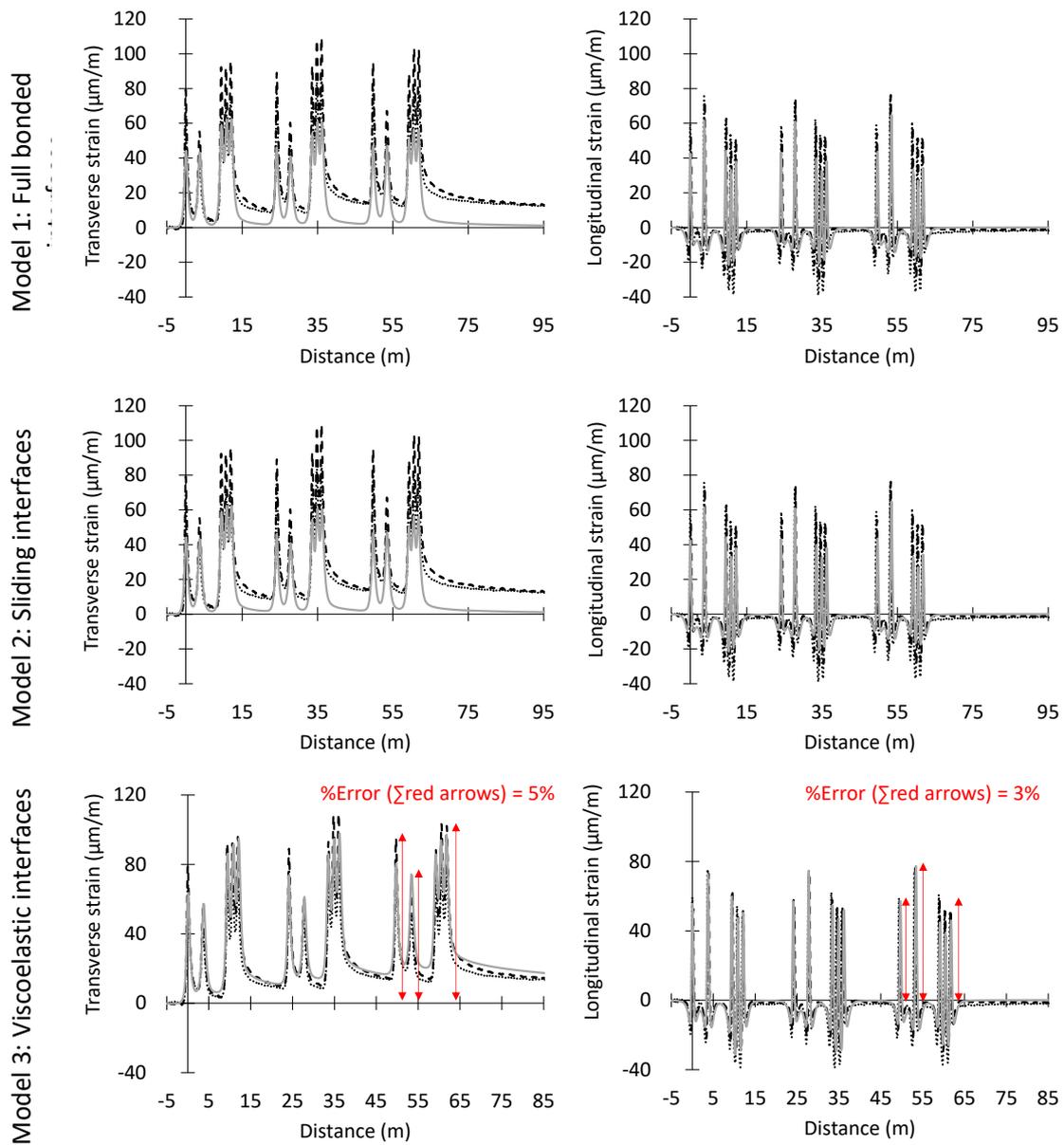


Fig. 2. Comparison of measured strains with modelling results - Fully loaded trucks (40-44 ton) in platoon configuration. Lateral deviation (wandering) = 0.04 m. Summer campaign. 40 km/h.

Step 2: Parametric study

After the validation of the model, a parametric study was conducted to evaluate the effect of the following parameters:

- Load per tire in the trailer tridem axle (see Table 2): 40 kN, 27.5 kN, and 15.7 kN.

- Temperature: -25°C, -5°C, 15°C, 35°C and 55°C.
- Truck speed: 40 km/h, 60 km/h and 80 km/h.
- Inter-truck time gap: 0.5 s, 2.0 s and 3.5 s.
- Base course thickness: 10 cm, 15 cm and 20 cm.
- Lateral deviation of the trucks in the platoon (wandering), with two cases:
 - Lateral deviation of all three trucks = 0 cm, Wandering of the platoon = 0 cm.
 - Lateral deviation of truck 1 = 0 cm, Lateral deviation of truck 2 = -20 cm, Lateral deviation of truck 3 = +20 cm, Wandering of the platoon = 40 cm.

Table 2. Load cases considered in the parametric study.

Axle	Wheel type	y (m) Lateral position of the platoon for Truck 1, Truck 2, and Truck 3 = 0 cm	x (m) distance from the first axle for each truck	Load levels										
				Level 1			Level 2			Level 3				
				Axle	Per tire	Total	Axle	Per tire	Total	Axle	Per tire	Total		
				(kN)	(kN)	(ton)	(kN)	(kN)	(ton)	(kN)	(kN)	(ton)		
Steer	315/80 R = 22.5	0	0	44.5	44.5	43	44.5	44.5	36	44.5	44.5	29		
Drive	315/80 R = 22.5	0	3.7	51.0	25.5		51.0	25.5		36	51.0		25.5	47.1
		-0.352			25.5			25.5			25.5			
Trailer tridem	385/65 R = 22.5	-0.016	5.7	120.0	40.0		82.5	27.5		36	47.1		15.7	
		-0.016	1.4		40.0			27.5			15.7			
		-0.016	1.4		40.0			27.5			15.7			

Note Table 2: Based on (Committee, 1997).

Effect of temperature

To evaluate the effect of temperature changes on pavement response, Fig. 3 shows the variation of the maximum transverse strain at the bottom of the asphalt base course with temperature, when the load in the trailer tridem axle of each truck in individual and platoon configuration is 40 kN. The results show that:

- The transverse strains decrease according temperature decrease. Under 15°C the effect of using platoons starts to be less important. For example, preferring the traffic of platoons (composed by 3-trucks at 40 km/h with inter-truck distances of 0.5 s) at 15°C instead of at 35°C can reduce the maximum transverse strains in about 80%.
- In most of the cases, platoons produce higher maximum strains than individual trucks, especially at high temperatures and reduced inter-truck time gaps. For example, the maximum increase in the graph reaches 24 % (versus the strain under individual trucks), for a time gap of 0.5 s at 40 km/h and 55°C, when the trailer tridem axle is loaded at 40 kN.

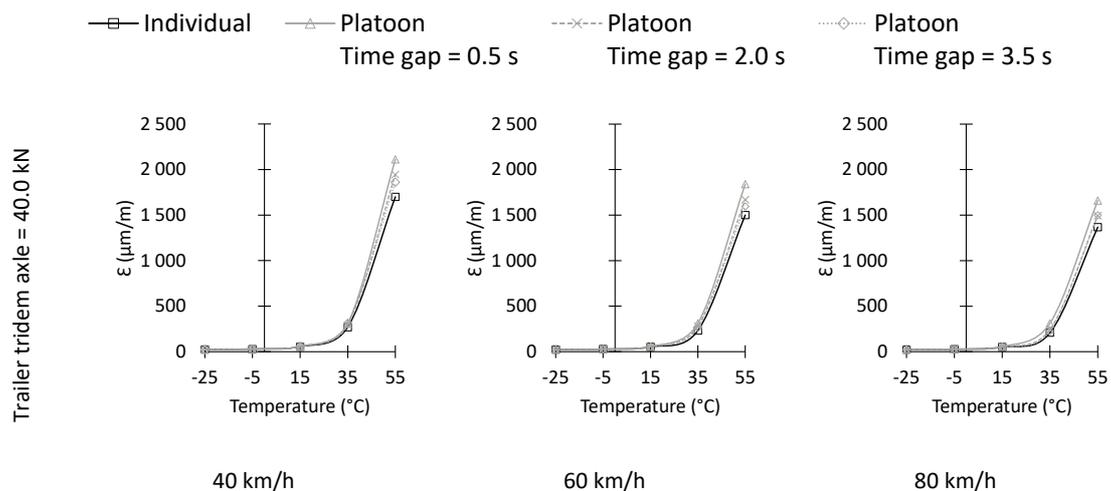


Fig. 3. Maximum transverse strain at the bottom of the base course for trucks in individual/platoon configuration and for different temperatures. Lateral deviation (wandering) = 0 cm. Load per tire in the trailer tridem axle = 40 kN.

Effect of lateral deviation variation

To characterise the effect of including a lateral deviation in the platoon, Fig. 4 shows an example of the transverse strain values obtained at the bottom of the asphalt base course when trucks 2 and 3 pass with a lateral deviation of ± 20 cm, representing a total lateral

wandering of 40 cm. As the figure shows, the inclusion of wandering reduces the strain values obtained during the passage of truck 2 and truck 3, distributing the damage over a wider surface along the pathway of the truck.

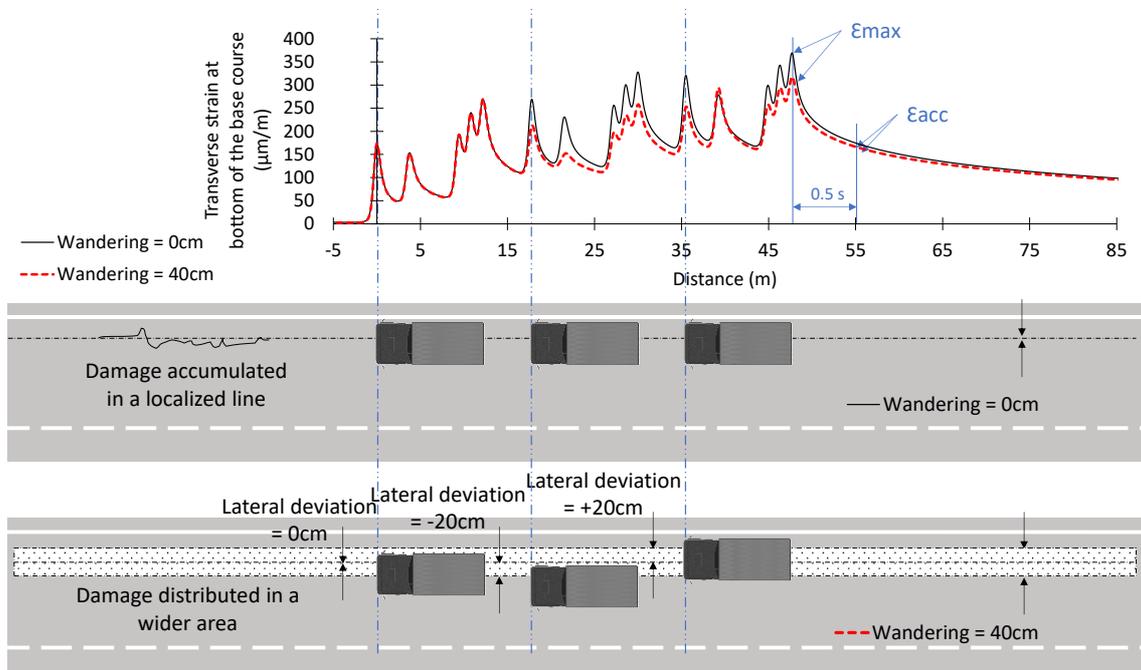


Fig. 4. Example of transversal strains obtained with and without lateral wandering (40 km/h, 35°C, Load per tire in the trailer tridem axle = 40 kN).

From Fig. 5 it is quantified that, the inclusion of a wandering of 40 cm for this example at different temperatures can reduce the maximum values obtained for the tridem axle of truck 3 between 1% and 17%. Recognising that fatigue laws are power equations generally based on these maximum values, the fatigue damage could be considerably reduced by including wandering patterns in the platoon. It is important to notice that at high temperatures, the strain reduction is much higher. This means that the introduction of a wandering pattern, to reduce pavement damage, will be more effective at high temperature.

Fig. 5 also shows that, in terms of accumulated strains obtained 0.5 s after the passage of the platoon, the values obtained for all the cases are reduced (from 1% to 75%) when wandering is applied. Here it is important to remark that despite the higher

reductions calculated at low temperatures, the strain values are considerably lower (in the order of E-01) in comparison to the ones obtained at high temperature (in the order of E+03). This means that the values could be considered almost the same, supporting that platooning at low temperatures do not represent a change in the performance of the pavement in comparison to the current traffic configurations.

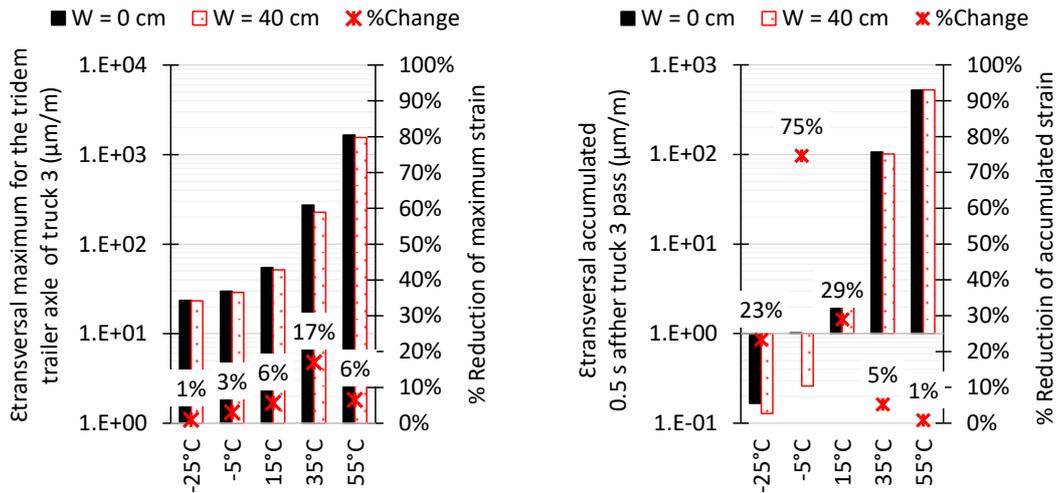


Fig. 5. Effect of increasing wandering (40km/h, inter-truck time gap = 0.5 s, Load per tire in the trailer tridem axle = 40 kN).

Effect of load level and inter-truck time gap

To describe the effect of the load level and inter-truck time gaps, Fig. 6 shows the transverse strain values calculated at the bottom of the asphalt base course for the case of truck with a trailer tridem load per tire of 15.7 kN, 27.5 kN and 40 kN traveling at 40 km/h in platoon configuration, when the temperature in the asphalt layers is 55°C. As shown in similar studies (Mateos & Snyder 2002), the transverse strains increase linearly when the trucks loads are increased (27.5 kN and 40 kN per tire in the trailer tridem axle) and the rest of parameters are kept constant.

The maximum transverse strain values are obtained under the trailer tridem axle of the third truck at load levels 1 and 2 (27.5 kN and 40 kN per tire in the trailer tridem

axle). For level 3 (15.7 kN per tire in the trailer tridem axle), the maximum values are obtained under the drive axle. In all the load cases, the maximum strain values increase with the reduction of the inter-truck time gap, which means a reduction of the rest periods.

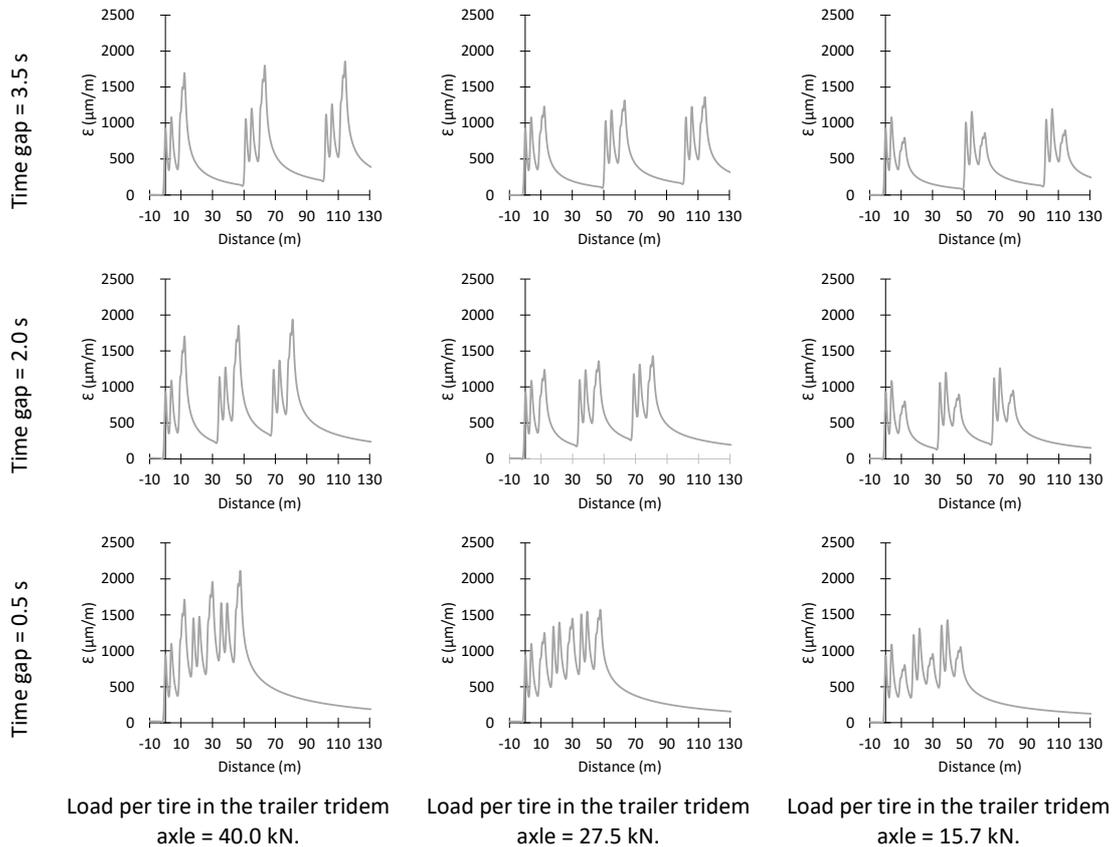


Fig. 6. Transverse strain values at the bottom of the base course for 40km/h and 55°C. lateral offset (wandering) = 0 cm.

Fig. 7 shows the maximum transverse strain values obtained for the trailer tridem axle of truck 3 in the platoon for the three load conditions and time gaps of analysis. Based on Fig. 7, different platoon strategies could be considered to keep the same strains as produced by trucks in individual configuration, for example:

- Reduce the total load of the trucks (red line). This means the distribution of the loads in the trailer tridem axle. For example, at 55°C and with inter-truck time

gaps of 0.5 s the load of the trailer tridem axle should be reduced from 40 kN to around 31 kN (23%).

- Increase inter-truck time gaps (blue line). For example, at 55°C (very extreme temperature condition), to have the same maximum strain than individual trucks with 40 kN per tire in the trailer tridem load, it is necessary to increase the inter-truck time gaps from 0.5 s to 3.5 s (7 times) and also to reduce the load per tire in the trailer tridem axle to around 36 kN (10%).

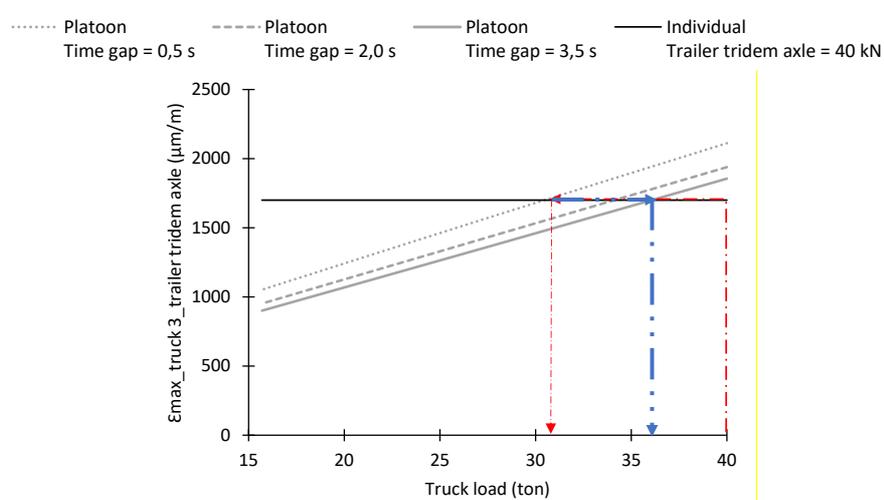


Fig. 7. Maximum transversal strain for trailer tridem axle of truck 3 (55°C, Load per tire in the trailer tridem axle = 40 kN, 40km/h, for individual truck and platoons, with different time gaps).

Variation of the number of trucks in platoon configuration

To evaluate the effect of the number of trucks driving in platoon, Fig. 8 shows the maximum strain values obtained at the bottom of the asphalt base course depending on the number of trucks forming the platoon, for trucks loaded with 40 kN per tire in the trailer tridem axle. The calculations correspond to a speed of 40km/h, lateral deviation of 0 cm and time gaps of 0.5 s, 2.0 s and 3.5 s. As the figure shows, the maximum transverse strain values seem do not change at 15°C or lower temperatures for trucks in platoon configurations, in comparison to individual trucks. At 35°C and 55°C however,

the strain values increase with the number of trucks, following a nearly logarithmic relationship. The rate of increase is higher at 55°C and when the time gap is reduced. For example, in comparison to the individual truck configuration, the values are 37% higher at 55°C for platoons of 6 trucks with inter-trucks time gaps of 0.5 s, and 40 kN per tire in the trailer tridem axle.

According to a case study carried out by Subtask 4.4.2 of ENSEMBLE, entitled “Understanding the convoy practice to forecast the adoption of platooning”, around 26% of current heavy vehicles are already grouping in convoys of 2 to 11 trucks with inter-truck time gaps of about 2.0 s. This means that to evaluate the real impact of platoons on road structures, this existing practice should be considered. It also means that a certain percentage of penetration of platoons could probably be allowed, without increasing the damage of pavement structures.

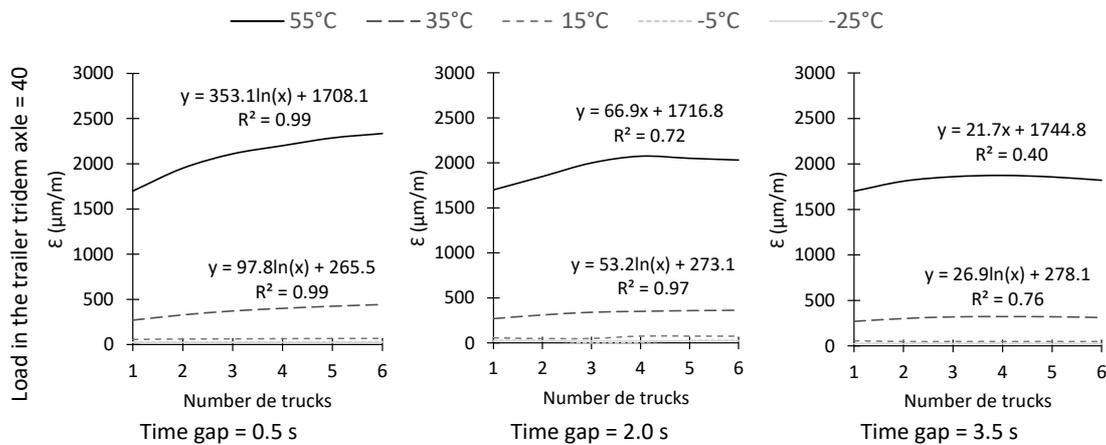


Fig. 8. Variation of the maximum transverse strains at the bottom of the asphalt base course according to the number of trucks in the platoon. Load per tire in the trailer tridem axle = 40 kN. Truck speed = 40km/h, Lateral deviation (wandering) = 0 cm.

Variation in the thickness of the asphalt layers

To determine the effect of varying the thickness of the asphalt layers, Fig. 9 shows the maximum transverse strain values obtained for both individual and platoon conditions (with different inter-truck time gaps), when the asphalt base course thickness varies

from 10 cm to 25 cm. The results show that, at -25°C the strain values obtained for individual and platoon truck configurations are practically the same (despite the variation in the truck speed and inter-truck time gaps), indicating a predominantly elastic behaviour of the asphalt layers. The differences between strain values increase at higher temperatures, and with the reduction of the inter-truck time gaps.

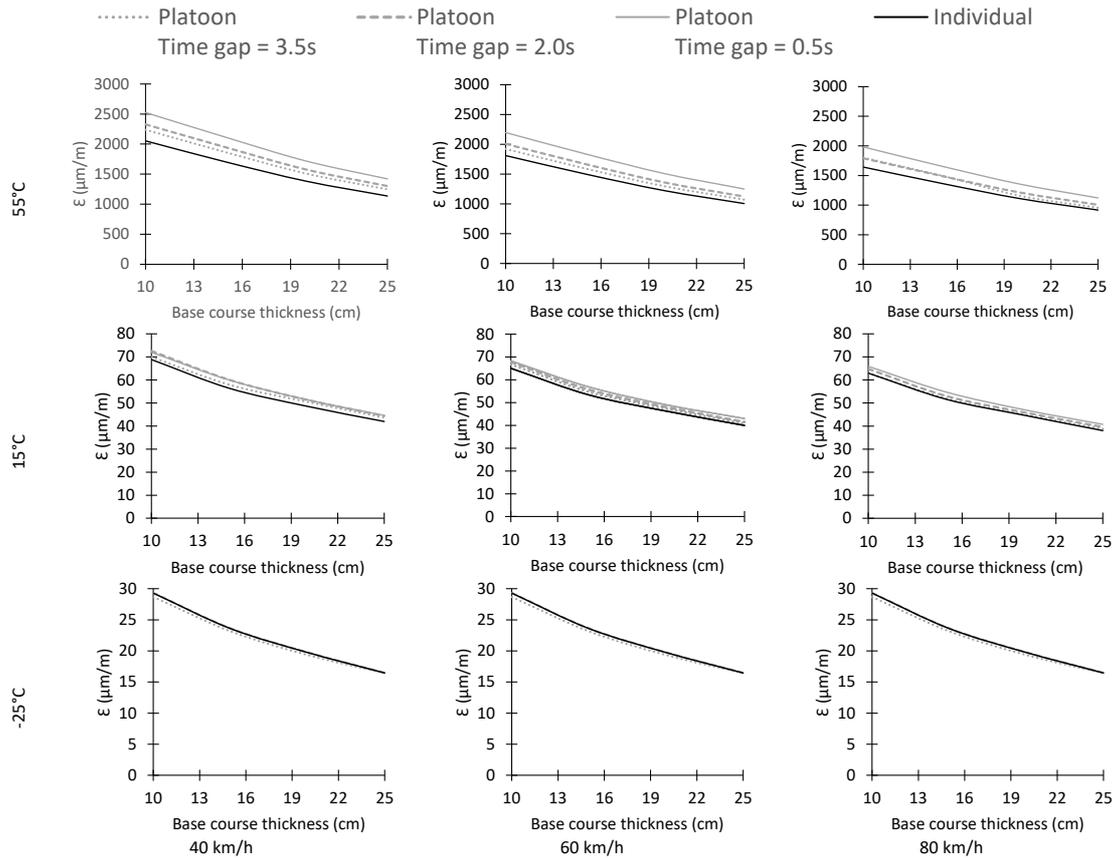


Fig. 9. Maximum transverse strains at the bottom of the asphalt base course according to base course thickness. Load per tire in the trailer tridem axle = 40 kN. Lateral deviation (wandering) = 0 cm.

Fig. 10 shows the transverse strain values obtained at the bottom of the base course for the individual truck configuration for different temperatures, and the corresponding estimation of the thickness needed to obtain the same strain values for the platoon truck configuration according to the inter-truck time gap according the obtained in Fig. 9. The results indicate that:

- At low temperature (-25 °C), no change of thickness is needed for the platoon configurations.
- The increase of thickness is more important as the temperature increases, and further rises with the reduction of the inter-truck time gap. The maximum thickness increase obtained is 5 cm (36 %), for a temperature of 55 °C and a time gap of 0.5 s.
- This increase of the base course thickness can be reduced from 36% to around 12% by adding a wandering of 20 cm at 55°C and with an inter-truck time gap of 0.5 s.

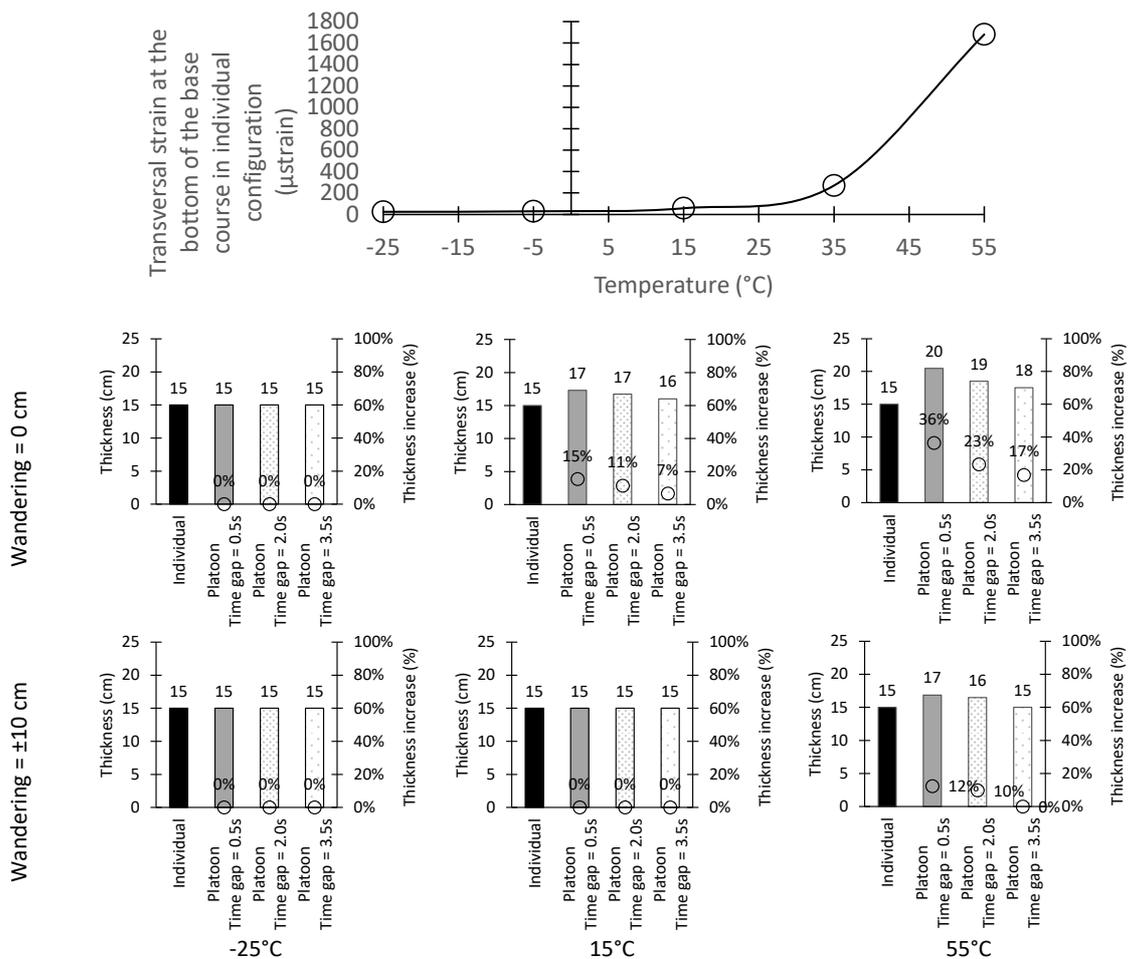


Fig. 10. Maximum transverse strains at the bottom of the asphalt base course for different temperatures, and thickness increase needed to keep the same strain level for the platoon configurations. Load per tire in the trailer tridem axle = 40 kN. Truck speed = 40km/h.

Conclusions

This paper presents the validation of a numerical model reproducing the structural responses obtained on a real scale instrumented test section, subjected to individual and platoon truck load configurations. The simulations indicated that a visco-elastic model, taking also into account thin visco-elastic layers, simulating the behaviour of layer interfaces, is able to predict with a good accuracy the response of the bituminous pavement under platoon loading.

Then, the validated model was used to analyse the influence of different parameters related to the loading of platoons: inter-truck time gap, lateral deviation and number of trucks in the platoon, truck speed, asphalt layers thickness, pavement temperature and level of truck loading. It can be concluded that:

- At low temperatures, there is practically no difference between the response of the pavement under single trucks, and under platoon configurations, for the different time gaps. At higher temperatures (above 15 °C), however, due to the viscoelastic response of the pavement, strains produced by platoons tend to increase, compared with those produced by a single truck.
- This effect can be also reduced by increasing the time gap between successive trucks. For example, for the pavement structure analysed in this study, when the load per tire in the trailer tridem axle was 40 kN and pavement temperature 55°C, the maximum transversal strain values obtained after the passage of the last truck in the 3-truck platoon traveling at 40 km/h, can be reduced by 8% if the time gap is increased from 0.5 s (inter-truck distance = 5,6 m) to 2.0 s (inter-truck distance = 22.8 m).
- Because pavement response is very sensitive to axle loads, a slight reduction of axle loads could help reduce the maximum strains at the bottom of the asphalt

layers under trucks in platoon configuration. For the case of study presented in this document, reducing the load per tire in the trailer tridem axle from 40.0 kN to 27.5 kN, can reduce the maximum strains produced by the last truck in the 3-truck platoon by about 26% at 55°C when the inter-truck time gap is 0.5 s.

- Similarly, the inclusion of a lateral deviation (wandering) reduces the maximum strains produced by the platoon. For example, in the case study presented in this document, including a lateral deviation of ± 20 cm in the platoon (wandering = 40 cm) can reduce the maximum transversal strains for truck 3 by around 23% at 35°C, with trucks traveling at 40km/h and inter-truck time gaps of 0.5s.
- If no restrictions are applied to the platoon configurations, platooning can increase pavement damage, and can require to increase the thickness of asphalt layers, to keep the same pavement fatigue life. For the studied pavement, the simulations indicated that, in the worst cases, a thickness increase of 3 to 5 cm could be required. However, the parametric study has shown that this impact can be considerably reduced by adapting parameters like maximum axle loads, inter-truck distances or lateral wandering between the trucks in the platoon.
- Increasing the number of trucks in platoon formation can increase the maximum strain values produced in a pavement when pavement temperatures are above 15°C, and inter-trucks time gaps are reduced. However, traffic studies show that even at present, part of the trucks circulating on highways are forming convoys. Therefore, additional studies, considering this fact are needed, to estimate the real impact of the introduction of platoons, and the platoon penetration that could be allowed without considerably changing the fatigue life of existing pavement structures.

Finally, the results presented in this paper concern only predictions of maximum strains in the pavement layers. Further research, based on laboratory fatigue tests, is also planned to improve the model used to predict pavement fatigue life under multiple loads, in order to predict more accurately the impact of platooning, not only on maximum strain levels, but also on pavement service lives. Another future perspective of this study is to use the data from the full-scale experiment to predict the effect of platoons on asphalt pavement rutting.

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Disclosure statement

The authors report there are not competing interests to declare.

References:

Bajwa, R., Coleri, E., Rajagopal, R., Varaiya, P., and Flores, C., 2017. Development of a Cost-Effective Wireless Vibration Weigh-In-Motion System to Estimate Axle Weights of Trucks. *Computer-Aided Civil and Infrastructure Engineering*, 32(6).

Bridgestone. (2020). *Truck Tire Data Book*. Version 20.1.

Chabot, A., Chupin, O., Deloffre, L., and Duhamel, D., 2010. ViscoRoute 2.0 A: Tool for the Simulation of Moving Load Effects on Asphalt Pavement. *Road Materials and Pavement Design*.

Chailleux, E., Ramond, G., Such, C., and De La Roche, C., 2006. A mathematical-based master-curve construction method applied to complex modulus of bituminous materials. *Road Materials and Pavement Design*, 7.

Chailleux, E., 2021. Viscoanalyse App (V2.0). Université Gustave Eiffel. <https://viscoanalyse-database.ifsstar.fr/>

- Chandra, S., and Nguyen, A., 2020. Freight truck emissions reductions with connected vehicle technology: A case study with I-710 in California. *Case Studies on Transport Policy*, 8(3).
- Chen, F., Song, M., and Ma, X., 2020. A lateral control scheme of autonomous vehicles considering pavement sustainability. *Journal of Cleaner Production*.
- Chen, F., Song, M., Ma, X., and Zhu, X., 2019. Assess the impacts of different autonomous trucks' lateral control modes on asphalt pavement performance. *Transportation Research Part C: Emerging Technologies*.
- Committee, C. 333 M., 1997. Interim Report on European Pavement Design Methods.
- Duong, N. S., Blanc, J., Hornych, P., Bouveret, B., Carroget, J., and Le feuvre, Y., 2018. Continuous strain monitoring of an instrumented pavement section. *International Journal of Pavement Engineering*, 8436, 1–16.
- European Commission Directorate General Transport., 2001. *Cost 334 Effects of Wide Single Tyres and Dual Tyres*. Final Report of the Action (Issue November).
- Gungor, O. E., and Al-Qadi, I. L., 2020a. All for one: Centralized optimization of truck platoons to improve roadway infrastructure sustainability. *Transportation Research Part C: Emerging Technologies*.
- Gungor, O. E., and Al-Qadi, I. L., 2020b. Wander 2D: a flexible pavement design framework for autonomous and connected trucks. *International Journal of Pavement Engineering*.
- Gungor, O. E., She, R., Al-Qadi, I. L., and Ouyang, Y., 2020. One for all: Decentralized optimization of lateral position of autonomous trucks in a platoon to improve roadway infrastructure sustainability. *Transportation Research Part C: Emerging Technologies*.
- Huet, C., 1965. *Etude par une méthode d'impédance du comportement viscoélastique des matériaux*. Université de Paris.
- Leiva-Padilla, P., Blanc, J., Trichet, S., Salgado, A., Hammoum, F., and Hornych, P., 2022. Comparison of the response of an instrumented pavement section under individual and platoon truck loading. *International Journal of Pavement Engineering*, 1–22.
- Leiva-Padilla, P., Blanc, J., Salgado, A., Hammoum, F., and Hornych, P., 2022. Fatigue Life Predictions for a European Pavement Test Section Subjected to Individual and Platoon Truck Configurations. *Transportation Research Record: Journal of the Transportation Research Board*, 036119812110654.
- Marsac, P., Blanc, J., Chupin, O., Gabet, T., Hammoum, F., Garg, N., and Nguyen, M. L., 2020. *Optimization of truck platoon wander patterns based on thermo-viscoelastic simulations to mitigate the damage effects on road structures*. In *Lecture Notes in Civil Engineering: Vol. 96 LNCE*.

Mateos, A., and Soares, J. B., 2015. Validation of a dynamic modulus predictive equation on the basis of Spanish asphalt concrete mixtures. *Materiales de Construcción*, 65(317).

Mateos, A. and Snyder, M. B., 2002. Validation of flexible pavement structural response models with data from the Minnesota road research project. *Transportation Research Record*, 1806.

Noorvand, H., Karnati, G., and Underwood, B. S., 2017. Autonomous vehicles: Assessment of the implications of truck positioning on flexible pavement performance and design. *Transportation Research Record*.

Rana, M. M., and Hossain, K., 2021. Simulation of autonomous truck for minimizing asphalt pavement distresses. *Road Materials and Pavement Design*.

Sayegh, G., 1966. *Variation des modules de quelques bitumes purs et bétons bitumineux*. Université de Paris.

Song, M., Chen, F., and Ma, X., 2021. Organization of autonomous truck platoon considering energy saving and pavement fatigue. *Transportation Research Part D: Transport and Environment*, 90.

Taylor, A. H., Droege, M. J., Shaver, G. M., Sandoval, J. A., Erlien, S., and Kuszmaul, J., 2020. Capturing the Impact of Speed, Grade, and Traffic on Class 8 Truck Platooning. *IEEE Transactions on Vehicular Technology*, 69(10).

Vahidi, A., and Sciarretta, A., 2018. Energy saving potentials of connected and automated vehicles. *Transportation Research Part C: Emerging Technologies* (Vol. 95).

Zhou, F., Hu, S., Chrysler, S. T., Kim, Y., Damjanovic, I., Talebpour, A., and Espejo, A., 2019. Optimization of Lateral Wandering of Automated Vehicles to Reduce Hydroplaning Potential and to Improve Pavement Life. *Transportation Research Record*.

Zhu, F., and Ukkusuri, S. V., 2018. Modeling the Proactive Driving Behavior of Connected Vehicles: A Cell-Based Simulation Approach. *Computer-Aided Civil and Infrastructure Engineering*, 33(4).