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## **Comparison of the response of an instrumented pavement section under individual and platoon truck loading**

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# **Comparison of the response of an instrumented pavement section under individual and platoon truck loading**

Trucks transiting in platoon configurations promise a reduction in traffic congestion, an improvement in road safety, as well as lower fuel consumption and greenhouse gases emissions. Considering that truck platoon configurations are new, it is necessary to describe the structural responses they can produce in the pavement. In this sense, the present study shows the results obtained from a full-scale experiment designed to evaluate the structural responses of a test track subjected to the passage of trucks under two configurations: individual and platoon. The experiment consisted of measuring the transversal and longitudinal strains produced at the level of the bituminous layers of the pavement structure when trucks under both test configurations are transiting at speeds of 40 km/h, 60 km/h, 70 km/h, and 80 km/h. In order to consider the weather influence, two test campaigns were performed, one during winter and the other in summer. The main conclusion of the study is that by managing inter-vehicle distances, truck speeds, wandering, time, and periods of circulation, it is possible to minimize the impact of truck platoon configurations on the pavement's structure performance.

Keywords: instrumented section; platoon; wandering; fatigue.

## **1. Introduction**

Before developing fully automated vehicles, truck platooning represents a promising solution to optimize road transportation. Allowing several trucks in convoy, to follow automatically a human-driven leader truck can present promising 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 (Alam et al. 2015; Bonnet and Fritz 2000; Eilers et al. 2015; Gungor et al. 2020; Gungor and Al-Qadi 2020a; Hoque et al. 2021; Humphreys et al. 2016; Konstantinopoulou, Coda, and Schmidt 2019; Ladino et al. 2021; Lammert et al. 2014; Hossein Noorvand, Karnati, and Underwood 2017; Robinson, Chan, and Coelingh 2010; Suzuki 2011; Thunberg et al. 2019; Tsugawa 2014; Tsugawa,

Jeschke, and Shladovers 2016). However, platooning also leads to channelization of traffic and a reduction of the recovery time between successive loads, which could lead to an increase of damage of pavement structures, reducing their service life and increasing their maintenance and rehabilitation costs (Chen et al. 2019; Chen, Song, and Ma 2020; Marsac et al. 2020; Hossein Noorvand et al. 2017; Zhou et al. 2019).

To address this issue, recent research studies mainly based on numerical simulation, have started to analyze the impact on pavement performance of the variation of specific variables representative of truck platoon configurations: distribution of the lateral wheel wander (Chen et al. 2019, 2020; Gungor et al. 2020; Gungor and Al-Qadi 2020b, 2020a; Marsac et al. 2020; H. Noorvand, Karnati, and Underwood 2017; Rana and Hossain 2021; Song, Chen, and Ma 2021; Zhou et al. 2019), inter-vehicle distances (Gungor et al. 2017, 2020; Gungor and Al-Qadi 2020a) and traffic distribution scenarios (Hoque et al. 2021; Rana and Hossain 2021). By using a mechanistic-empirical approach, some of those researchers determined the damage produced by platoons in terms of fatigue and accumulated deformation. The analysis agrees upon the need to control wandering (Gungor and Al-Qadi 2020a, 2020b; Rana and Hossain 2021; Zhou et al. 2019), inter-vehicle distances (Gungor et al. 2020) and to define exclusive lanes or times of the day for the transit of platoons (Hoque et al. 2021; Rana and Hossain 2021) in order to preserve the fatigue performance and self-healing capacities of the pavement, and reduce maintenance costs (Gungor et al. 2020; Gungor and Al-Qadi 2020a).

In the same line, and as a previous reference for the present study, Marsac et al. (2020) developed a model to evaluate the effects of multiple loads of truck platoons on road structures for different configurations of wander patterns, using the software ViscoRoute© 2.0. This software's capacity to evaluate the viscoelastic response under dynamic solicitations allowed to evaluate the aggressiveness produced by different truck

platoon configurations, in order to define a wandering pattern to be tested on a test track on site. According to the results of the study, including a wandering of 25 cm can reduce fatigue damage caused by a platoon configuration composed of three trucks by a ratio of 6, compared to a configuration without wandering.

In this context, this paper presents the results of a full-scale experiment carried out in Tarragona, Spain, to study the response of an instrumented pavement section, subjected to the transit of trucks traveling in individual and platoon configurations. A laser system was used to verify the speed, wandering, and inter-truck distances applied during testing. The platoon configuration used consisted of three trucks traveling in the same lane at inter-vehicle distances defined by a time gap of 0.8s. The test protocol involved the variation of the truck speed and the lateral wheel wander. Two test campaigns were carried out, the first one in the winter (January 2020) and the second one in the summer (August 2020), to consider the two extreme temperature conditions that characterize the weather in Tarragona.

This study is part of the research conducted in the European Project ENSEMBLE (ENeabling Safe Multi-Brand pLatooning for Europe), which main goal is “to pave the way for the adoption of multi-bran truck platooning in Europe to improve fuel economy, traffic safety and throughput” (Anon n.d.; Mascalchi, Coda, and Willemsen 2020).

## **2. Materials and methods**

### ***2.1. Pavement test section***

The test track used in this research is located in the facilities of the automotive company Applus IDIADA, in Tarragona, Spain. Applus IDIADA test track has been considered as the best in Europe, specially used in the design and development of test sections for

automotive industries from everywhere in the world. As shown in Fig 1, a 12 m long instrumented test section was built on this test track. The corresponding pavement structure is composed by three asphalt layers (4 cm thick wearing course, 6 cm thick base course and 15 cm thick subbase course) placed over a cement stabilized layer. The instrumentation placed in the test section consists of 24 strain gauges type KM-100HAS Tokyo Sokki Kenkyujo, for the measurement of the longitudinal strains (12 gauges) and transversal strains (12 gauges) at 10 cm and 25 cm depth from the pavement surface and 6 thermocouples, 3 of them placed at the bottom of each asphalt layer for two different locations. The strain gauges were placed at 0.85m, 1.05m, and 1.25m from the border of the lane. This configuration was selected to enable the lateral truck offset and wandering presented in Fig. 2, which was measured by using the laser system shown in Fig. 3. The laser system shown in Fig. 3 was composed by 4 lasers configured to manage and measure inter-truck distances, trucks speeds and wandering applied during testing. The instrumentation design was based on the evaluation of the bottom-up fatigue phenomena under individual and platoon truck configurations, which is related to the maximum strain in tension in the asphalt surface layers.

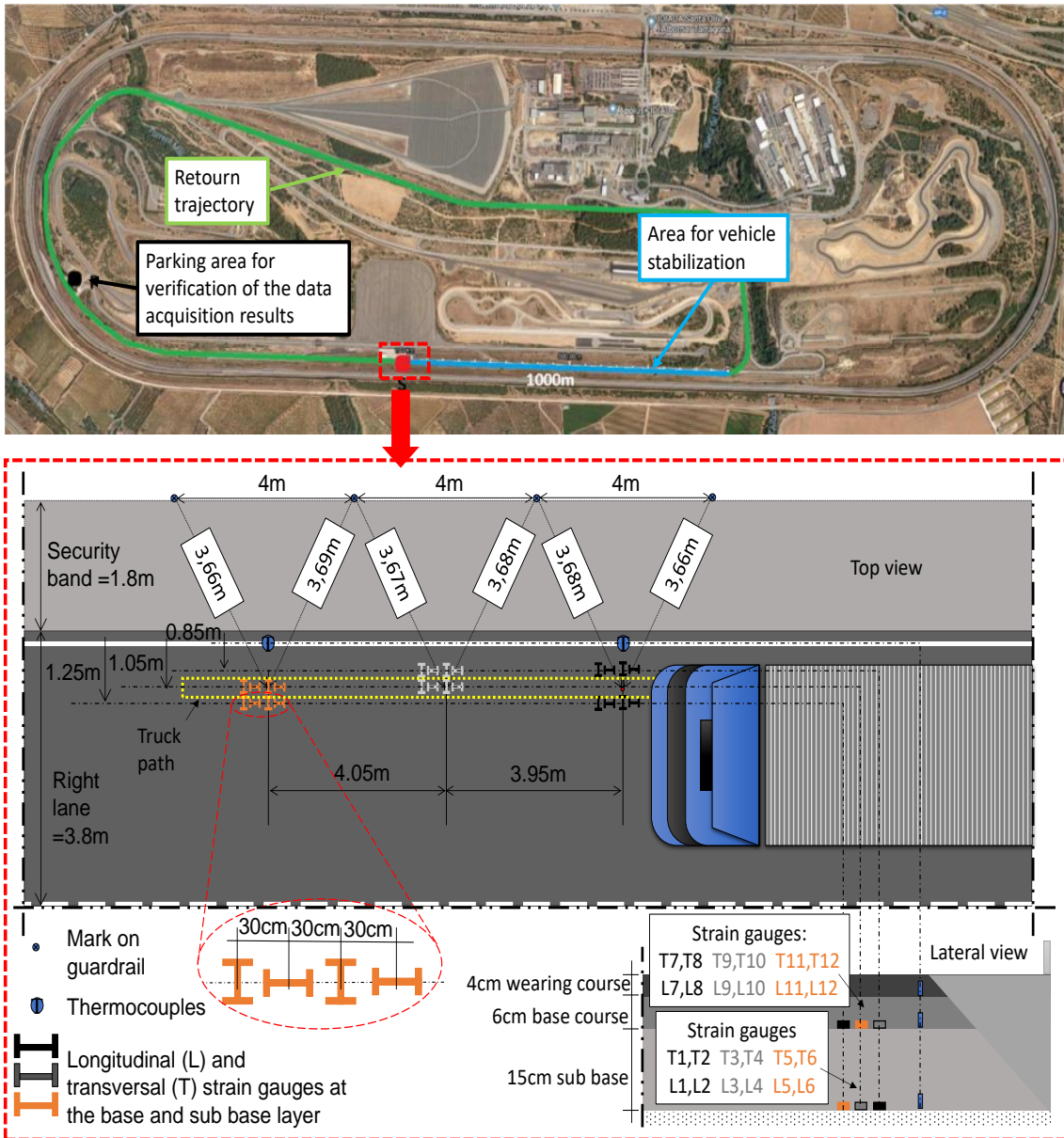


Fig. 1. IDIADA test track and instrumented test section.



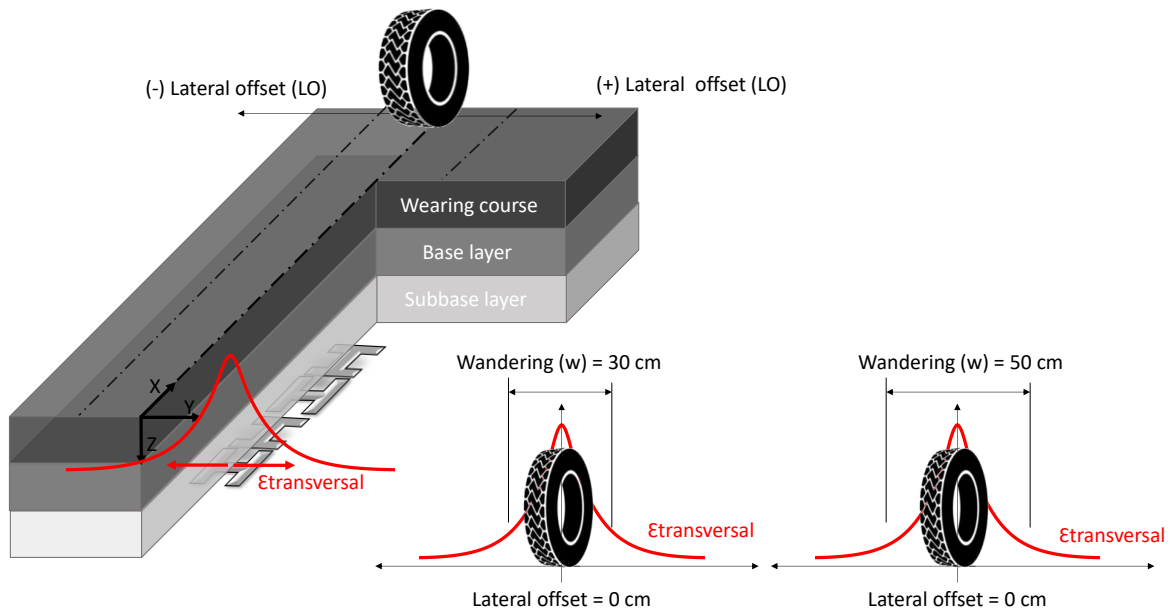


Fig. 2. Detail about the strain gauge position, lateral offset and wandering.

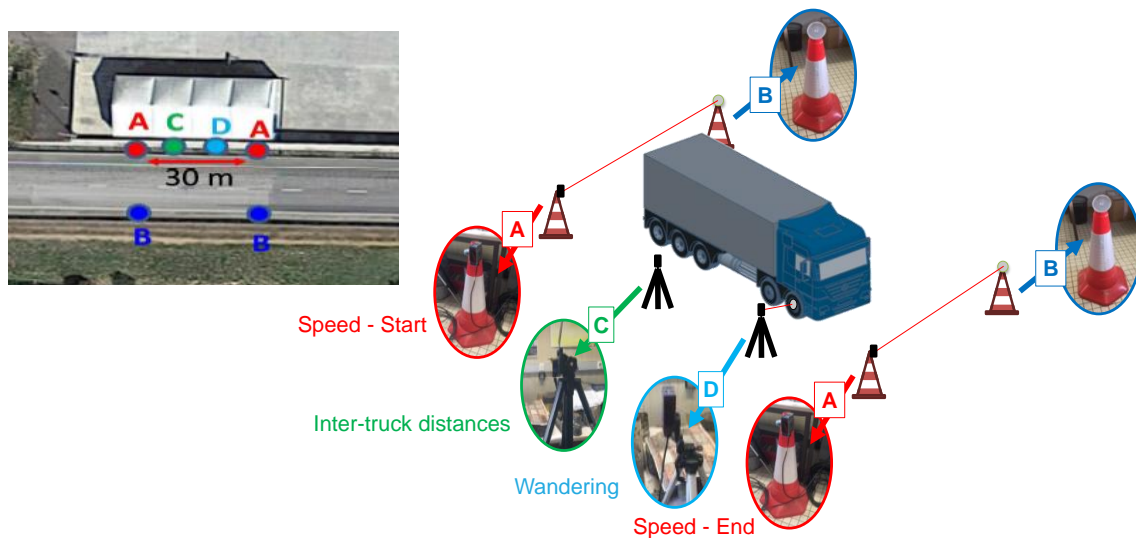


Fig. 3. Laser system used in the test.

## 2.2. Data collection details: testing protocol

The objective of the tests was to measure and compare the response of the pavement under individual and platoon truck configurations. The tests were performed with three 5-axle semi-trailer trucks of similar characteristics, with a total weight of ~40 tons, which details are shown in Fig 4.

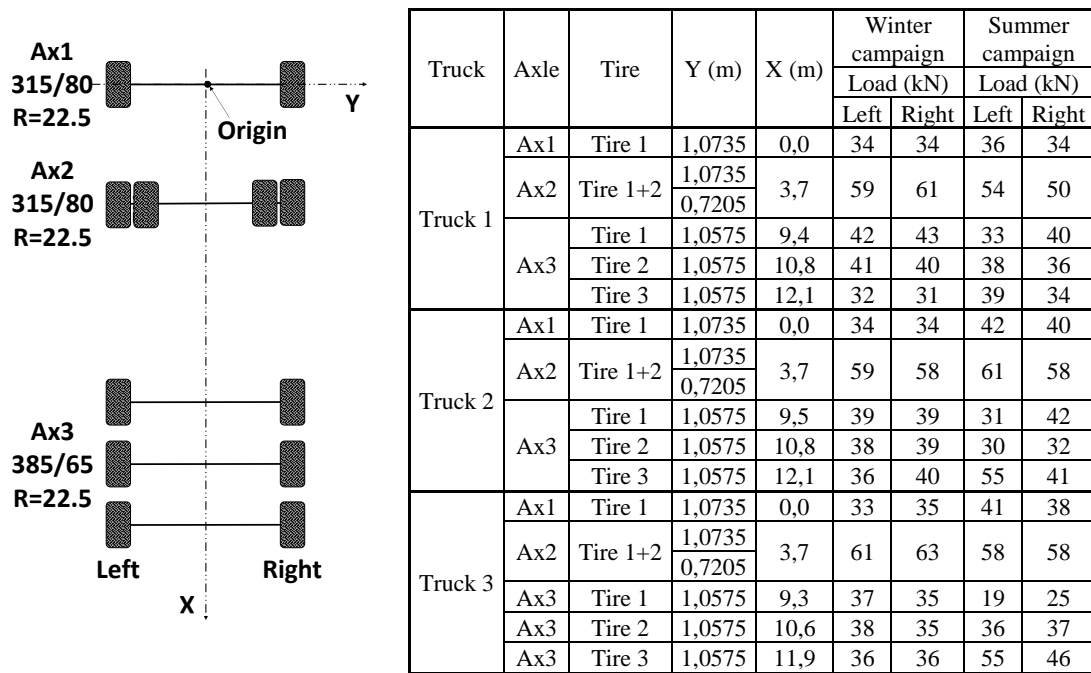


Fig. 4. Axle geometrical configuration and weight for each truck.

The test protocol considered the parameters shown in Table 1. Two test campaigns were performed: the first one in winter, in January 2020, and the second one in summer, in August 2020. During each campaign, the tests were carried out varying the truck speeds (40, 60, 70, and 80 km/h) and wandering (naturally produced along with testing), for the two truck configurations shown in Fig. 5: (1) Individual and (2) Platoon. In the Platoon truck configuration, a time gap of 0.8 s between the vehicles was applied to represent the minimum commercial values used in the adaptive cruise control systems, leading to inter-vehicle distances varying with the test speed.

During each test campaign, a total of 24 runs were performed with the trucks in the individual configuration and 20 passages in the platoon configuration. As shown in Table 1, the pavement response parameters measured were the longitudinal and transversal strains at the bottom of the base asphalt layer and of the subbase asphalt layer, as well as the pavement layer temperatures.

Table 1. Parameters evaluated in the experimentation.

Parameter	Characteristics
Pavement responses: horizontal strains	Depth of measurement: 10 cm (4cm of a wearing course + 6cm of a base layer) and 25 cm (4cm of a wearing course + 6cm of a base layer + 15 cm of a subbase layer). Direction of measurement: longitudinal (L) and transversal (T).
Truck speed	40, 60, 70 and 80 km/h. Measured with a laser system and verified from processing the strain data.
Wandering (w)	30 cm and 50 cm.
Lateral offset (LO)	From the center line of the lane: 0 cm.
Truck test scenarios	Individual configuration and platoon configuration.
Inter-truck distance (L)	Adjusted to a time gap of 0.8 s between trucks.
Campaigns	<p>Winter:</p> <ul style="list-style-type: none"> <li>• 11 of January 2020: <ul style="list-style-type: none"> <li>○ Individual Trucks</li> <li>○ Temperature: 10.3°C and 11.3°C respectively at 25cm and 10cm depth from the pavement surface.</li> </ul> </li> <li>• 12 of January 2020: <ul style="list-style-type: none"> <li>○ Platoon Configuration.</li> <li>○ Temperature: 8.3°C and 6.1°C respectively at 25cm and 10cm depth from the pavement surface.</li> </ul> </li> </ul> <p>Summer:</p> <ul style="list-style-type: none"> <li>• 29 of August 2020: <ul style="list-style-type: none"> <li>○ Individual Trucks</li> <li>○ Temperature: 27.5°C and 25.9°C respectively at 25cm and 10cm depth from the pavement surface.</li> </ul> </li> <li>• 30 of August 2020: <ul style="list-style-type: none"> <li>○ Platoon Configuration.</li> <li>○ Temperature: 25.7°C and 25.0°C respectively at 25cm and 10cm depth from the pavement surface.</li> </ul> </li> </ul>
Number of passages	<p>Winter:</p> <ul style="list-style-type: none"> <li>• Individual Truck: 4 speeds x 2 repetitions x 3 trucks = 24 passages.</li> <li>• Platoon Configuration: 4 speeds x 5 repetitions = 20 passages.</li> <li>• Total passages = 44.</li> </ul> <p>Summer:</p> <ul style="list-style-type: none"> <li>• Individual Truck: 4 speeds x 2 repetitions x 3 trucks = 24 passages.</li> <li>• Platoon Configuration: 4 speeds x 5 repetitions = 20 passages.</li> <li>• Total passages = 44</li> </ul>

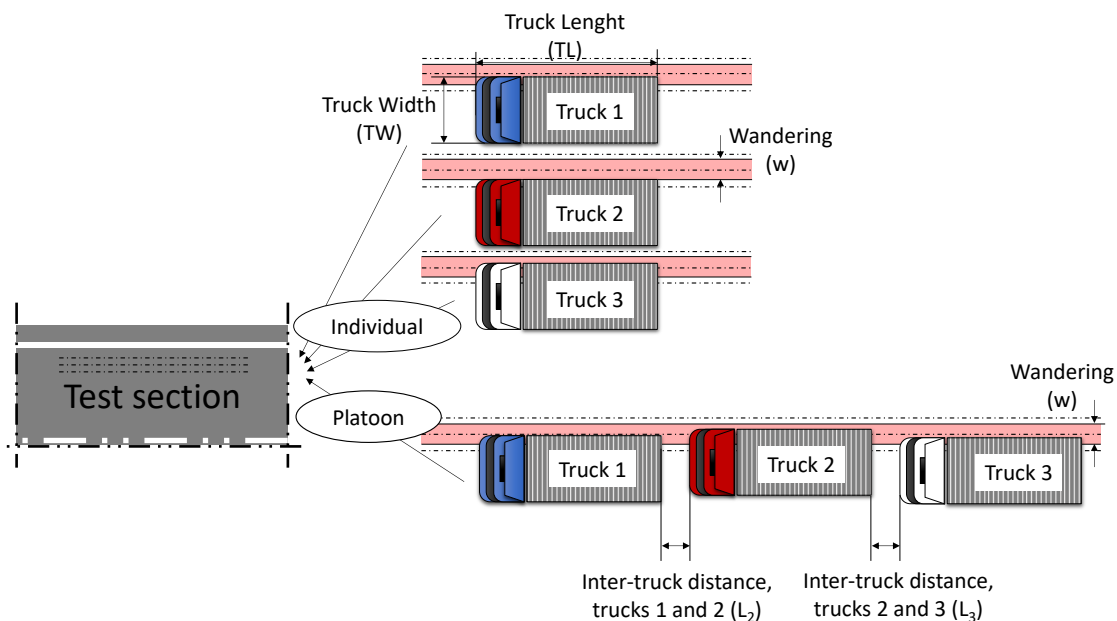


Fig. 5. Test scenarios: Individual and Platoon.

### **3. Discussion of results**

#### ***3.1. Description of the measured strain signals***

This paper will present only the data collected by the strain gauges placed at the bottom of the sub-base layer. Fig. 6 and Fig. 7 show examples of longitudinal and transversal strain signals recorded, by the passage of Truck 1 in individual configuration and during winter and summer campaigns (i.e. low and high temperature conditions), when the test speed was 60 km/h. Twelve strain gauges, located at the bottom of the sub-base layer, are presented: 6 transversal and 6 longitudinal, but located at different lateral positions. The results indicate that (1) the measured transversal strain signals change with the change in the lateral position of the wheels, even change its sign (extension or contraction) when a vehicle passes at different lateral positions relatively close to the sensors, (2) at high temperatures, the strain signals change significantly showing amplitudes much more higher, with transversal strains reaching values of approximately 110  $\mu$ strains at the bottom of the sub-base layer and closed to the wheels passage, (3) the shape of the transverse strain signals at the bottom of the bituminous layers is also modified, with a slow return to zero after loading, this delayed response is due to the viscoelastic behavior of the bituminous layers, and is more pronounced under the three rear axles of the vehicle and at high temperatures. Similar results have been previously observed in a study conducted on a real pavement (Duong et al. 2018). In this study, high extension strains have been measured at the bottom of the bituminous layer at high temperature (30°C), and similarly, a slow return to zero of the strains after loading was observed.

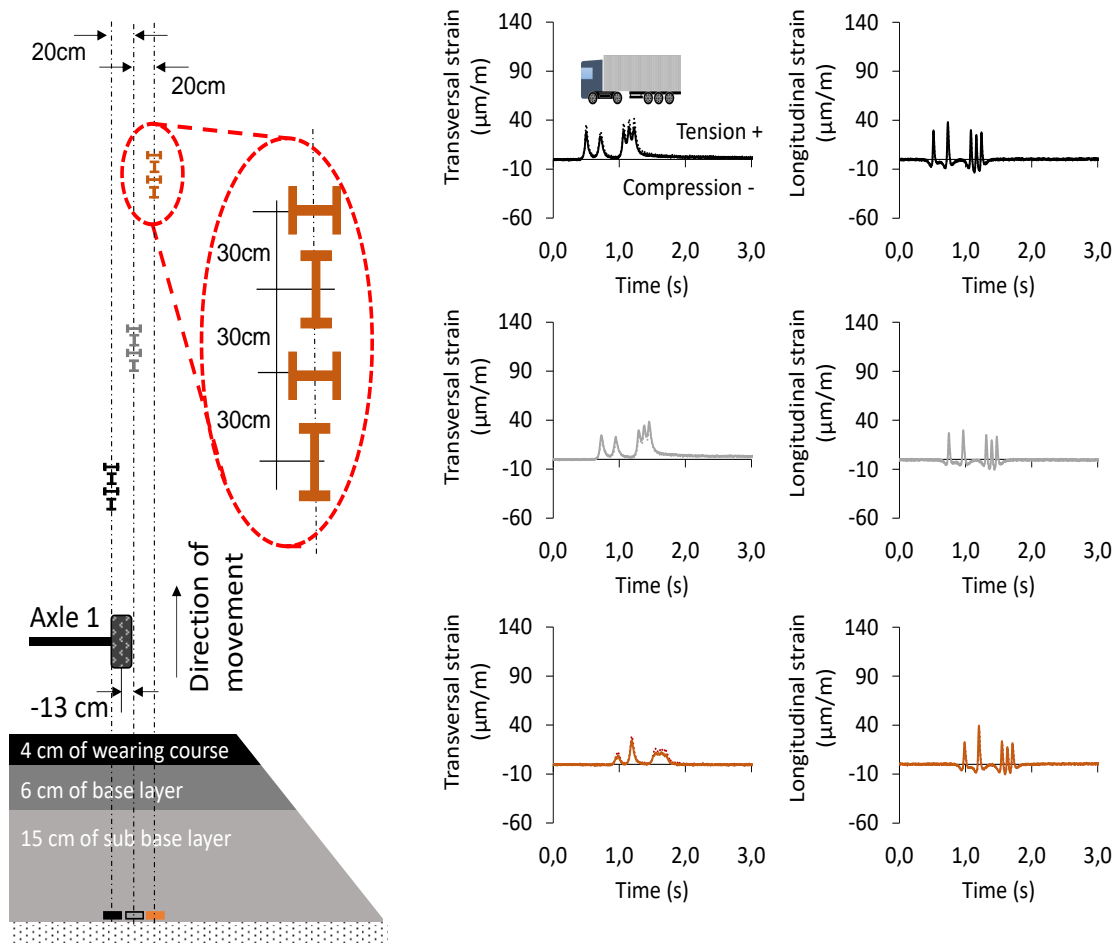


Fig. 6. Horizontal strains obtained from run 8 for Truck 1 under individual configuration (Winter campaign, Truck speed = 60km/h, Strain Gauges Depth = 25 cm, Y1 = 0.73m, truck distance from the central strain gauges set = -0,13cm).

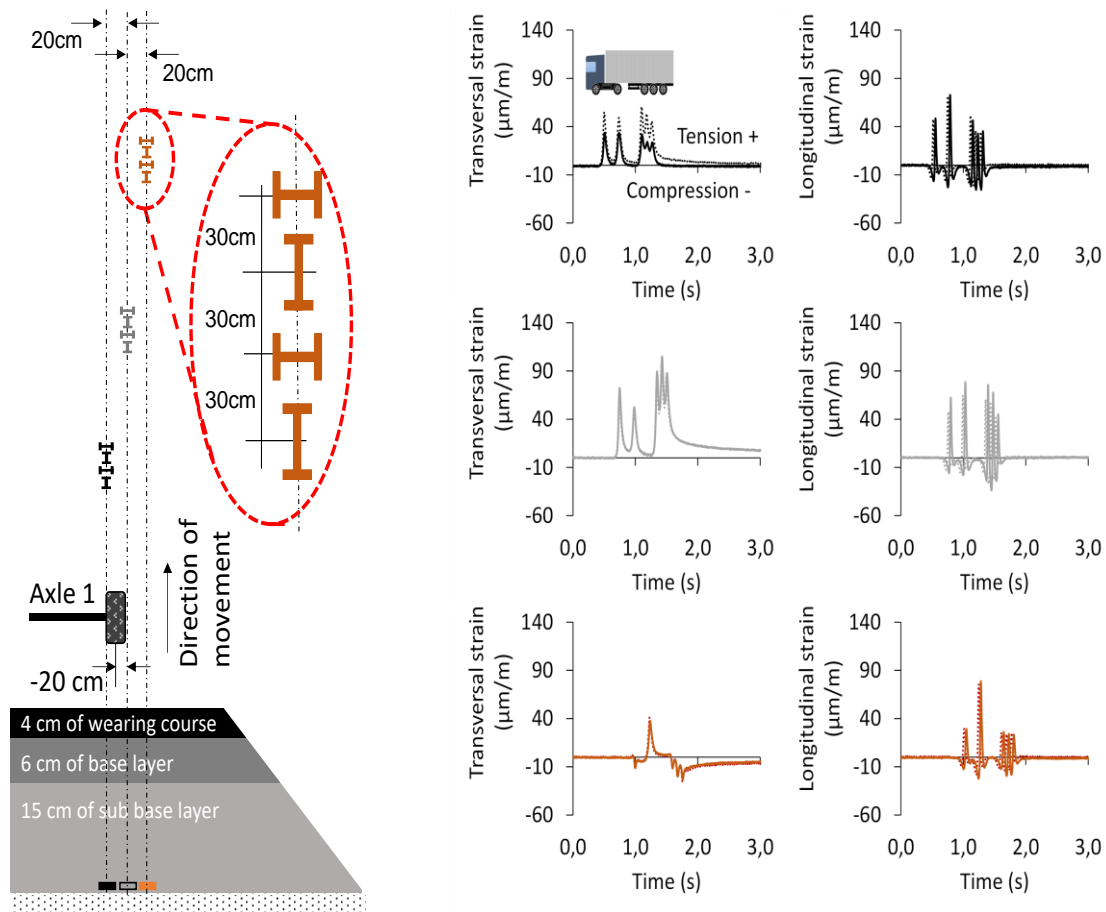


Fig. 7. Horizontal strains obtained from run 8 for Truck 1 under individual configuration (Summer campaign, Truck speed = 60km/h, Strain Gauges Depth = 25 cm, Y1 = 0.65m, truck distance from the central strain gauges set = -20cm).

Extending the illustration to the platoon configuration, Fig. 8 and Fig. 9 present examples of transversal and longitudinal strain signals obtained by the strain gauges T3, T4, L3, and L4 during run 38 for the winter campaign and run 32 for the summer campaign, at 70 km/h. During both runs, the lateral distance from the center strain gauge set was close to zero for each truck, with the purpose to capture the maximum strain values under the configurations tested. Considering that both figures are equally scaled in the y axis once again it is noticed that: (1) as for individual configuration, at low and high temperatures, the strains are in extension in both longitudinal and transversal directions, (2) at high temperatures, the strain signals change significantly: the strain amplitudes are much higher, with transversal strains reaching values of approximately 140 µstrains (instead of

40  $\mu$ strains at low temperature), (4) the shape of the transverse strain signals at the bottom of the bituminous layers is also modified, with a slow return to zero after loading due to the viscoelastic behavior of the bituminous layers, and is more pronounced under the three rear axles of the vehicle and at high temperatures.

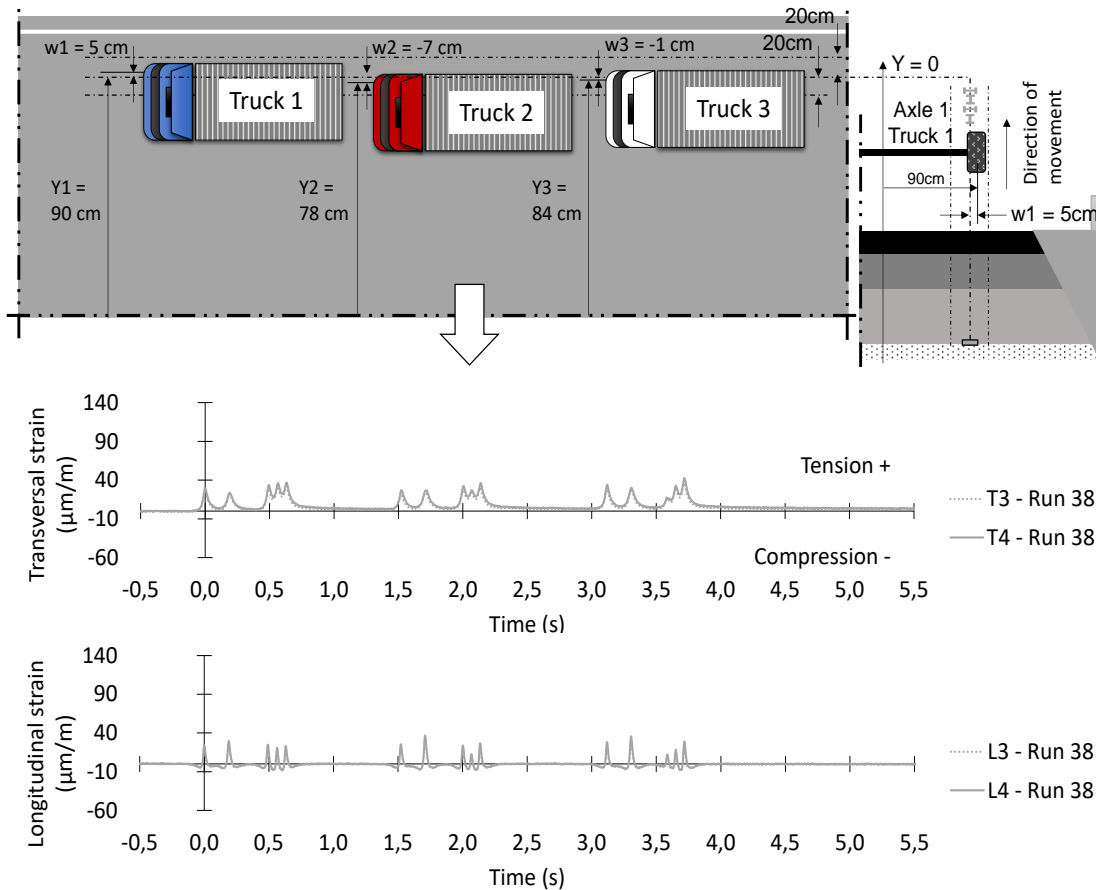


Fig. 8. Example of signal obtained for run 38 in the platoon configuration (winter campaign, strain gauges: T3, T4, L3 and L4, truck speed = 70km/h, equally distanced trucks from the central strain gauges set).

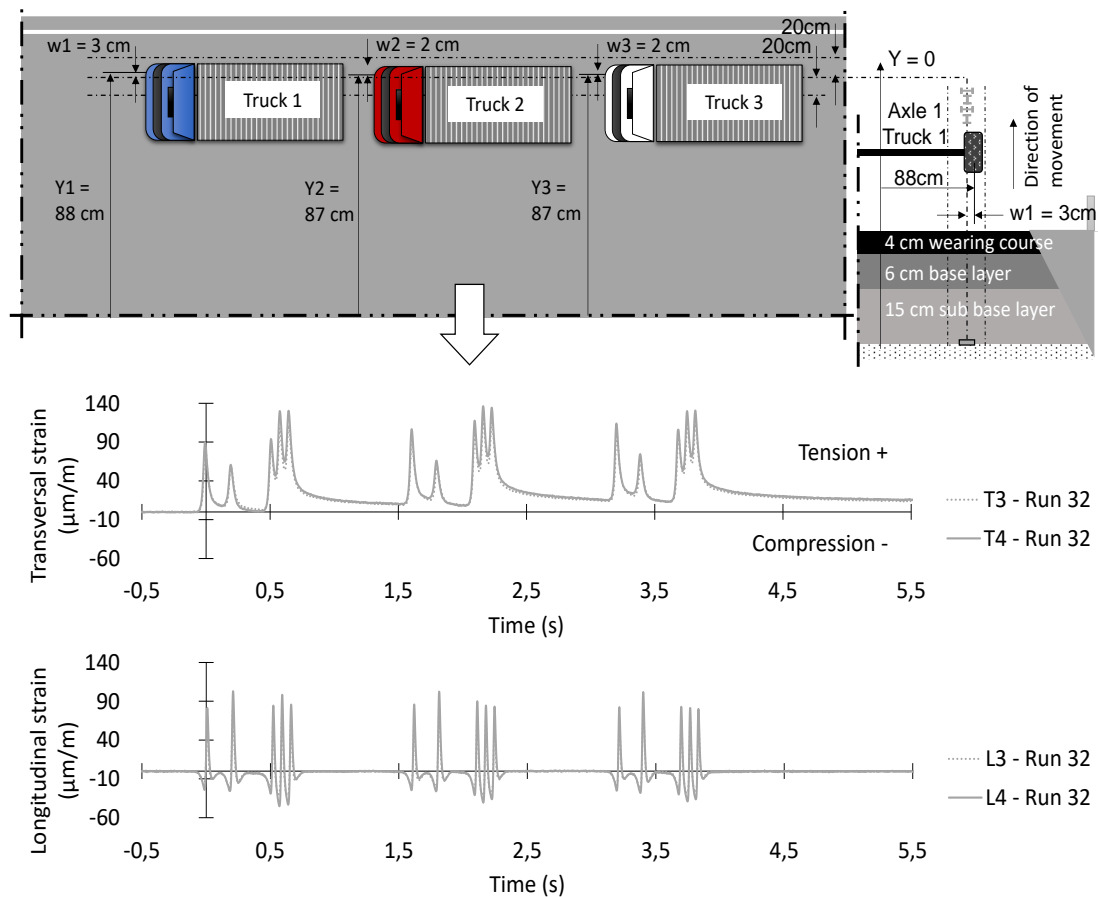


Fig. 9. Example of signal obtained for run 32 in the platoon scenario (summer campaign, strain gauges: T3, T4, L3 and L4, truck speed = 70km/h, equally distanced trucks from the central strain gauges set).

### 3.2. Data repeatability and reproducibility

To evaluate the repeatability of the data, as shown in Fig. 10, the strain measurements from runs 5 and 26 were selected to represent the following test conditions: use of the same operator (Truck 1), individual configuration, same lateral distance from the strain gauge, same test truck, similar strain gauges (T1, T2, L1 and L2) and short intervals of time between passages (run 5: 11/01/2020, 16:02; run 26: 12/01/2020, 10:11). The Analysis Of VAriance (ANOVA) performed according to the null hypothesis of equality among the average values of the maximum strains obtained for each axle, led to conclude that for a confidence level of 99%, there is a significant influence of the axle type but not of the run number (5 or 26), meaning good data repeatability during the test.



To evaluate data reproducibility, as shown in Fig. 11, the parameters considered were the following: individual configuration, same test section, same wandering, different operators (truck 1, truck 2, and truck 3), and different strain gauges. The ANOVA of the maximum strain values obtained for each axle led to conclude that, for a confidence level of 99%, there is a significant influence of the type of axle but not of the run number. This indicates a good reproducibility of the data collected.

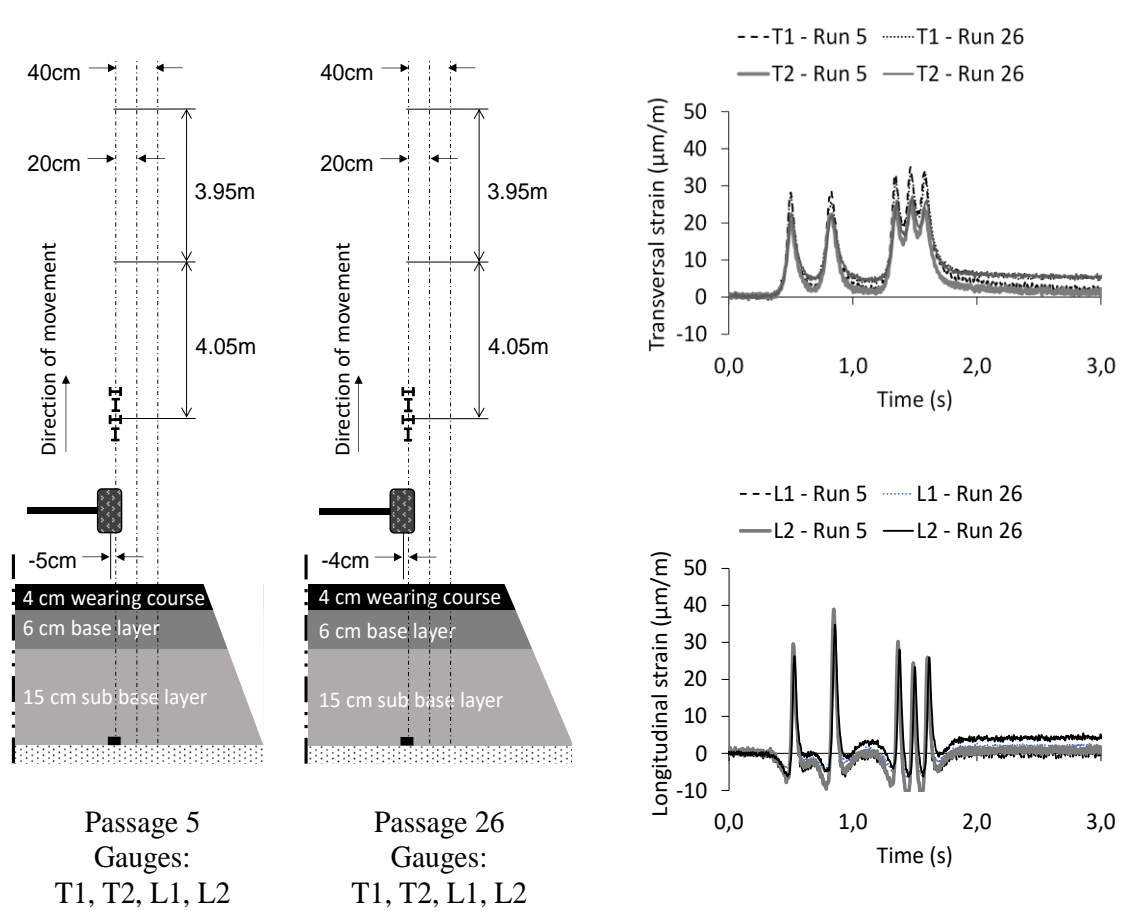


Fig. 10. Analysis 1: Repeatability, Truck 1, Truck speed = 60 km/h, Individual Configuration, Transversal (T) and Longitudinal (L) strain gauges, winter campaign.

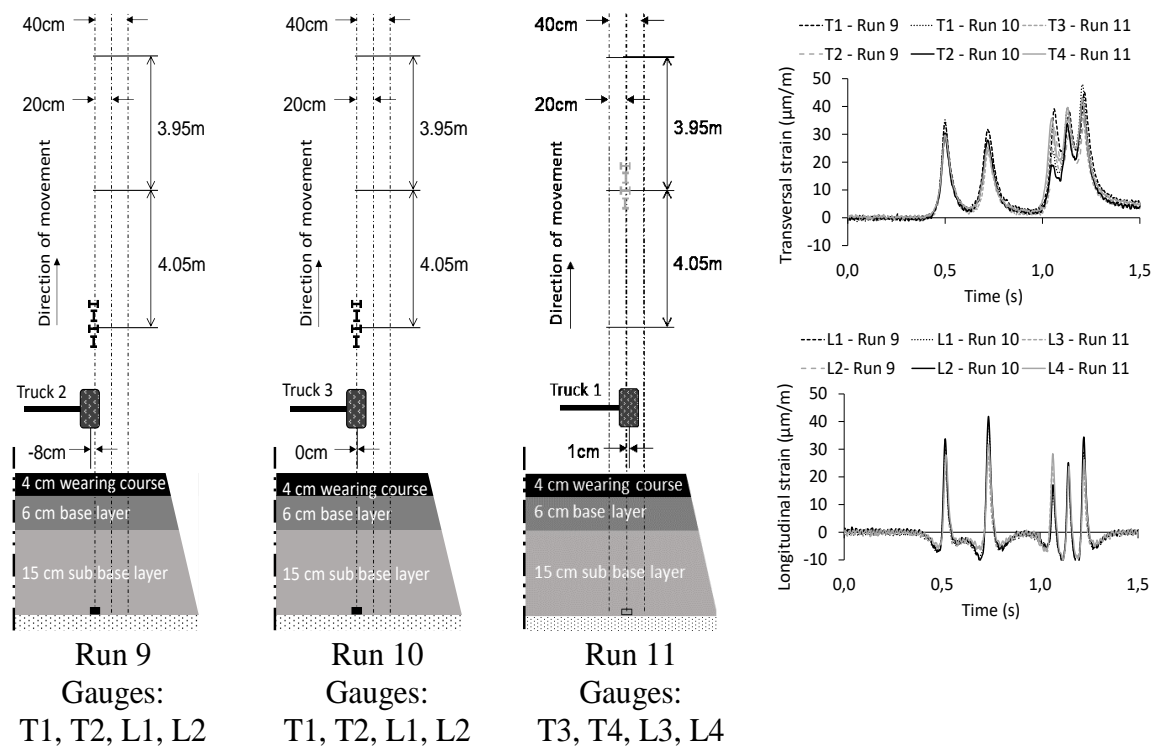


Fig. 11. Analysis 2: Reproducibility, considered truck speed = 60 km/h, winter campaign, Individual Configuration, Transversal (T) and Longitudinal (L) strain gauges.

### 3.3. Verification of test conditions using instrumentation and laser measurements

With the purpose to verify the correspondence between the truck speed applied during testing and the real speed conditions obtained, Fig. 12 and Fig. 13 show a comparison of the truck speeds obtained from the data collected with the laser system and the strain gauges, for both test campaigns. The visual analysis of the figure shows higher variation for a truck speed of 80 km/h which can be caused by the fact that platoon truck configurations are being produced by human drivers. Therefore, as test speeds increase, the difficulty for the truck drivers to keep constant inter-trucks distances increases. The ANOVA of the data concludes that for a confidence level of 95% the values are significantly the same for both systems. Table 2 shows the corresponding coefficients of

variation of the data, which are lower than 11%, indicating that the average values are homogeneous and representative for the sample.

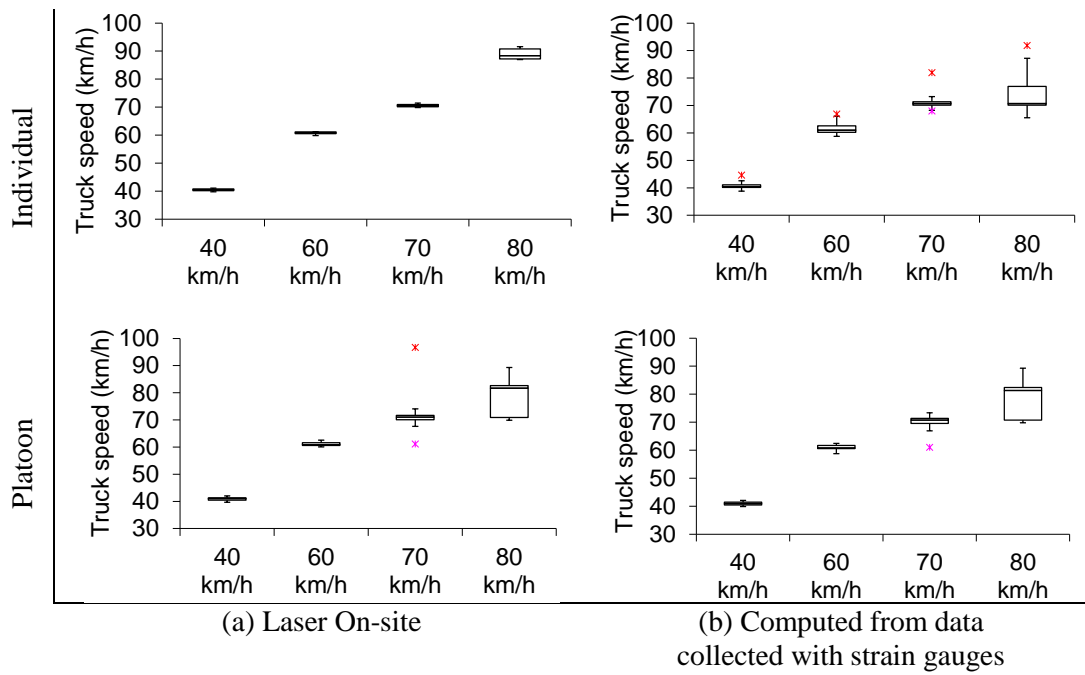


Fig. 12. Truck speeds for both individual and platoon configurations (winter campaign).

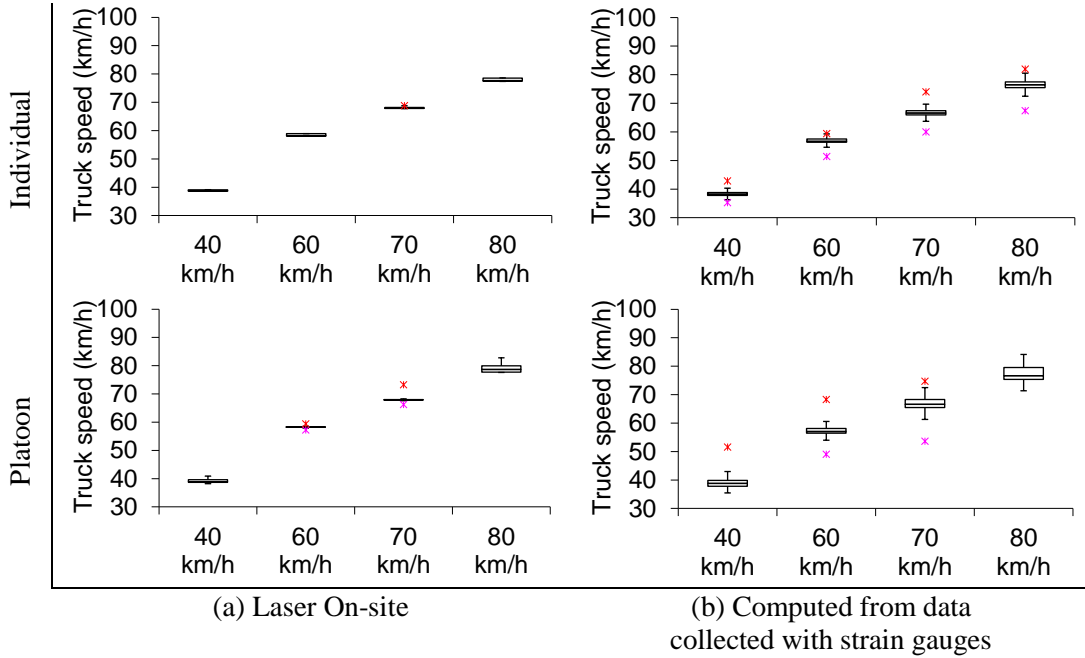


Fig. 13. Truck speeds for both individual and platoon configurations (summer campaign).

Table 2. Coefficients of variation of truck vehicle speeds.

Configuration	Coefficient of variation							
	Winter campaign				Summer campaign			
	40 km/h	60 km/h	70 km/h	80 km/h	40 km/h	60 km/h	70 km/h	80 km/h
Individual - Laser	1%	1%	1%	1%	1%	1%	1%	1%
Individual - Computed	3%	3%	4%	5%	3%	4%	4%	4%
Platoon - Laser	2%	2%	1%	11%	2%	1%	2%	2%
Platoon - Computed	2%	2%	11%	6%	6%	5%	6%	3%

Considering that the lateral distance between each strain gauge and each truck has certain variations during testing, Fig. 14 shows the corresponding histogram graph of lateral tire positions, which reveals that a high number of runs were done at positions between -30 cm and 0 cm, with a certain tendency to be located on the left side. By the form of the graph and considering the central limit theorem which establishes that the distribution of a sample tends to be normal as the size becomes larger, these values can be considered to follow a normal distribution centered on -17 cm with a standard deviation value of 20 cm. In this case, the values were only verified by the measurements done with the laser system.

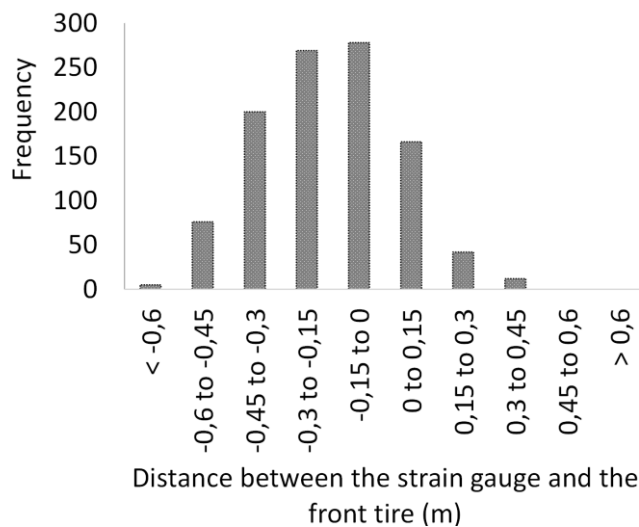


Fig. 14. Distance between the strain gauge and the front tire for the whole test conditions applied (campaign, truck, speed, load configuration).

Finally, Fig. 15 displays inter-truck distances measured with the laser system and computed from the strain signals obtained from pavement instrumentation. As shown in Fig. 16, these inter-truck distances have been obtained by maintaining a time gap of approximately 0,8 s between the trucks in the platoon configuration. As a consequence, inter-truck distances increase with increasing truck speed. The higher variation of inter-truck distances observed at higher truck speeds can be due to the fact that the vehicles were not automated but driven by human drivers, which had more difficulty to maintain constant inter-truck distances at high speed. Table 3 indicates the coefficients of variation of these inter-truck distances, which values are higher during the Summer Campaign. This can only be explained by the change of the truck drivers participating to the test campaigns.

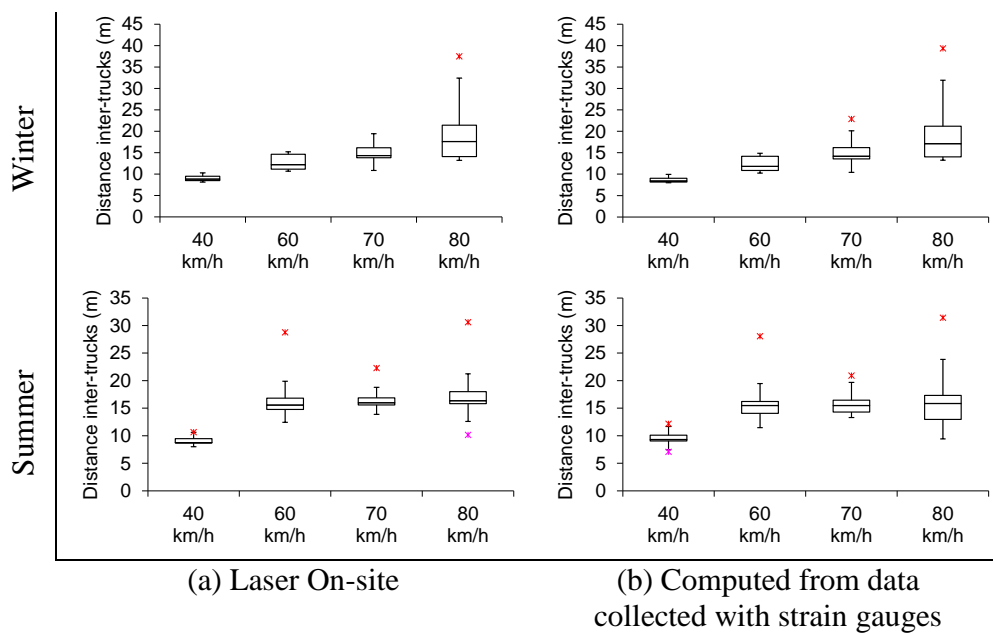


Fig. 15. Inter-truck distances for a time gap of 0.8 s in the platoon configuration.

Table 3. Coefficient of variation for inter-truck distance.

Configuration	Coefficient of variation							
	Winter campaign				Summer campaign			
	40 km/h	60 km/h	70 km/h	80 km/h	40 km/h	60 km/h	70 km/h	80 km/h
Platoon - Laser	8%	8%	15%	17%	10%	25%	15%	15%
Platoon - Computed	7%	7%	14%	20%	13%	29%	15%	41%

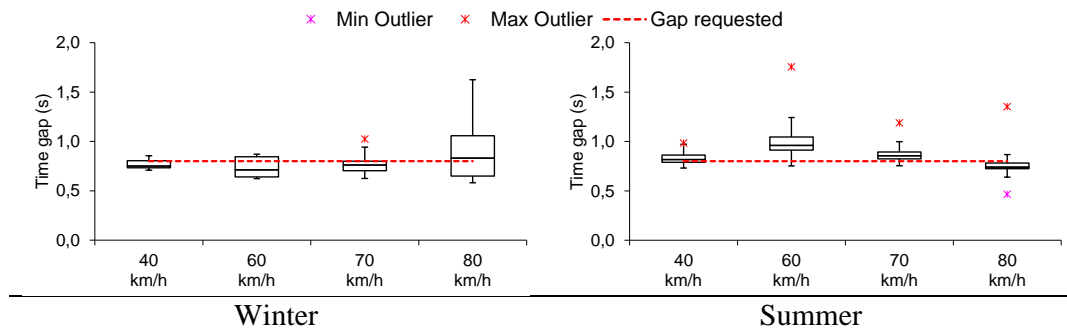


Fig. 16. Inter-truck time gaps in the platoon configuration.

### 3.4. Influence of the Platoon Configuration on pavement performance

Fig. 17 shows the critical tensile strain levels defined in this study, to treat the signals obtained from testing. These points were proposed to analyze ideal Platoon Configurations that could be implemented, with a view to avoid the reduction in the fatigue performance defined for the pavement structure during design. The first and second points correspond to the maximum values obtained under the pass of the first and second axle. The third point corresponds to the maximum strain under the pass of the tridem axle, and the fourth point to the accumulated strain registered 0.7 s after the passage of each truck. The value of 0.7 s was selected to enable comparisons with the Platoon configuration because the inter-truck time interval can be less than 0.8 s in some cases due to the variability experienced during the test.

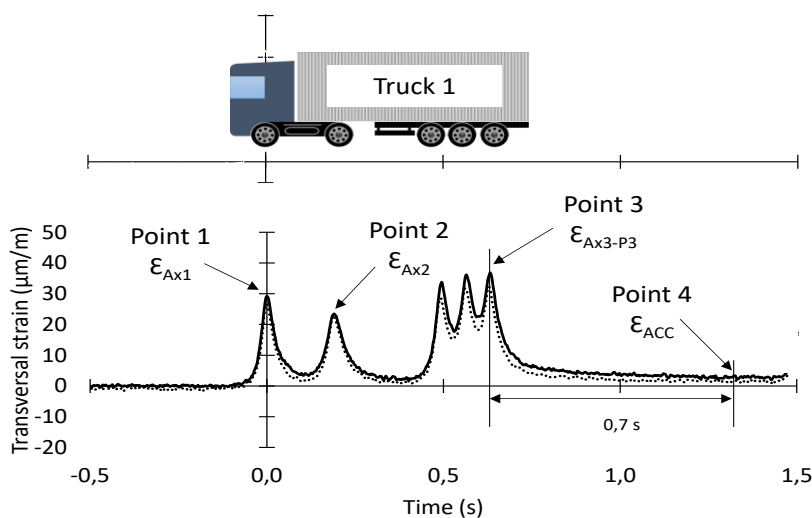


Fig. 17. Points of analysis of the strain signals used in this study.

#### *3.4.1. Mechanical responses at the critical strain levels*

Fig. 18 and Fig. 19 display the strain values obtained during the winter campaign for each critical strain level for individual trucks and platoon configuration, at 40, 60, 70 and 80 km/h. The order of magnitude of the critical strain levels are quite the same for individual trucks and platoon configuration (maximum of 50  $\mu$ strains and about 6  $\mu$ strains for accumulated strains). The results shown in both figures are referenced to the line at 0.85m from the centerline of the lane, which corresponds to the position of the central set of strain gauges, considered in this study as the position of zero lateral offset. Recognizing that, there were placed three set of strain gauges along the lateral position, the values shown in both figures corresponds to the real truck distance from each strain gauge set. In this sense, the distance from the center of each point was corrected by three factors: (1) the truck location, (2) the strain gauge location, and (3) the width of the tire in the sense of traffic.

With this correction, both figures show the decrease of the different critical strain values when the lateral position of the tires varies relatively to the position of each gauge. These figures show that for Axle 1 and Axle 3, the maximum strains were obtained at approximately  $\pm 11.25$  cm from the strain gauge, which fits with the 22,5 cm of the tire wide. The same behavior is produced for Axle 2 which by the dual configuration are in a wider area, approximately  $\pm 23$  cm. Going longer than this distance, the strain values decrease reaching zero at approximately 25 cm apart from the border of the tire. This means that increasing the lateral wandering can reduce significantly the number of times that the highest strain solicitations due to the pass of the truck, will be applied at a given point. The figures also show that, in comparison to the individual configuration, there are not considerably difference in the values obtained during the winter campaign.

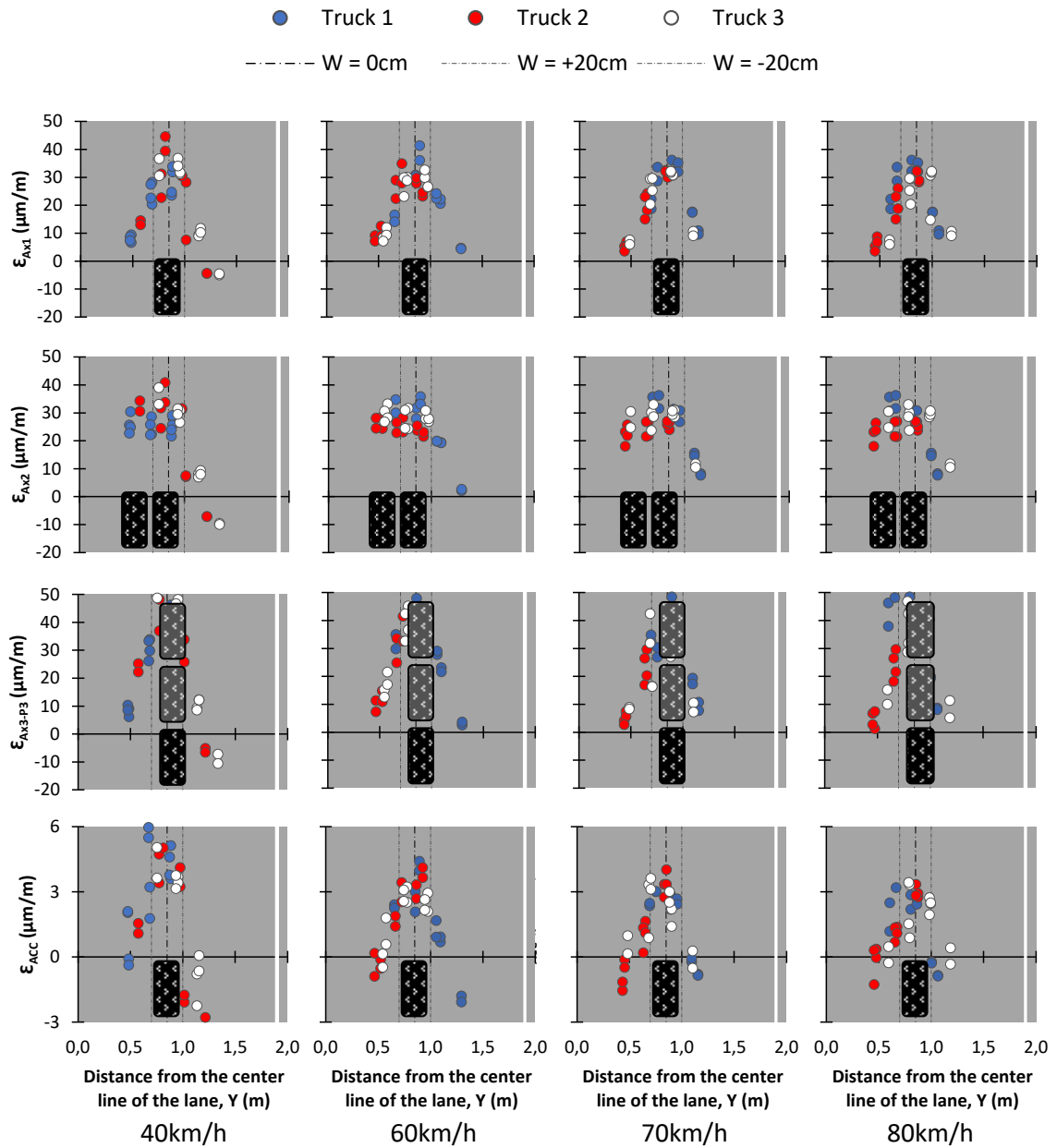


Fig. 18. Transversal strains at each point of analysis for the individual truck scenario (winter campaign).



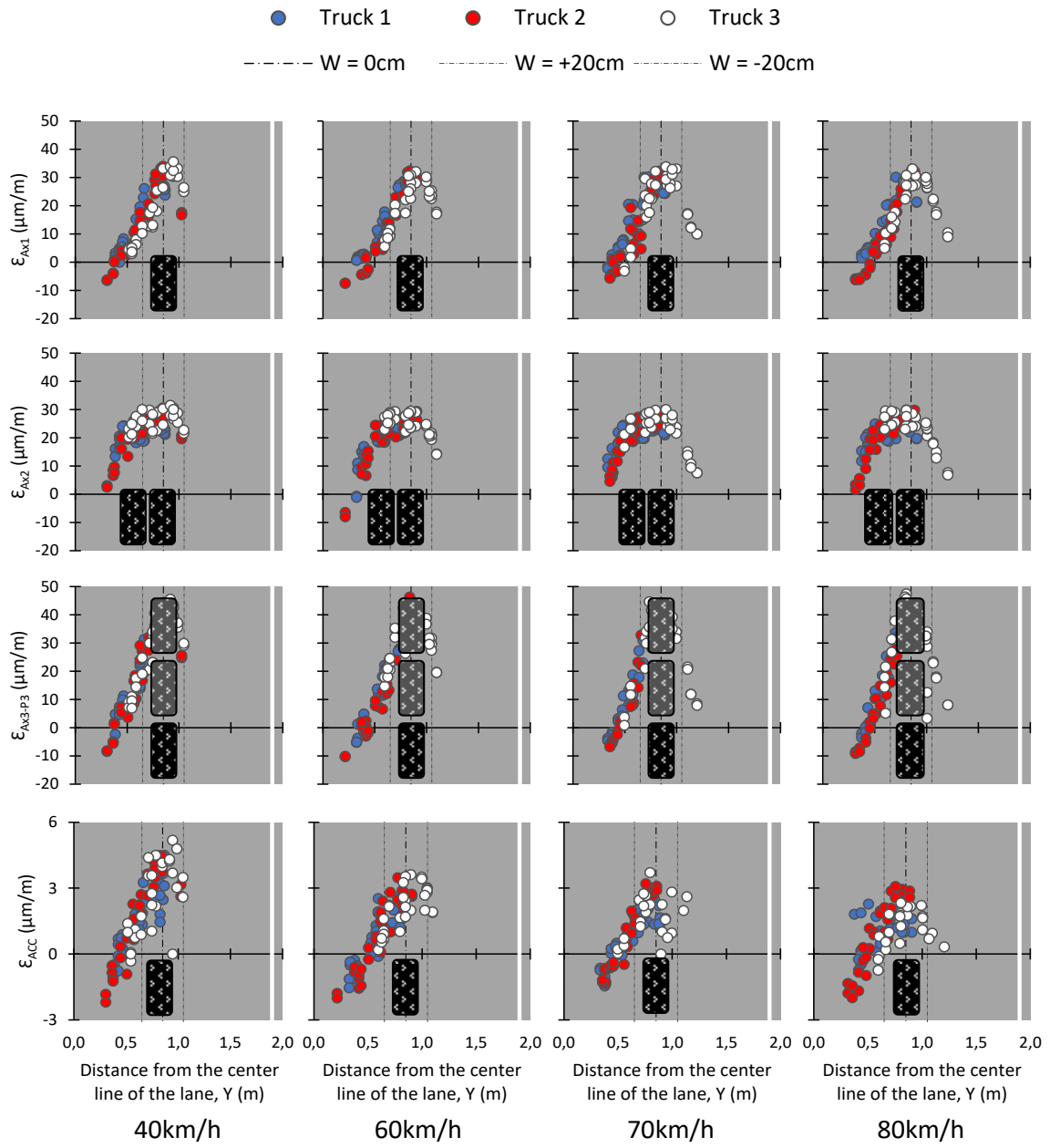


Fig. 19. Transversal strains at the points of analysis for the platoon configuration (winter campaign).

Similarly, Fig. 20 and Fig. 21 show the critical strain values obtained during the summer campaign, for each critical strain level, relatively to the line at 0.85m from the centerline of the lane. In comparison to the winter campaign, the curves show the same tendencies. However, the values have considerably increased, revealing differences between individual truck and platoon truck configurations. The maximum critical strain level is about 100  $\mu\text{strains}$  for individual trucks and 140  $\mu\text{strains}$  for platoon configuration and

the maximum accumulated strain value is about 15  $\mu$ strains for individual trucks and 35  $\mu$ strains for platoon configuration. It means that the higher temperatures produced during Summer reduce the pavement capacity due to the viscoelastic behaviour of the asphalt layers, making more important the damaging effect caused by the multi-load platoon configurations.

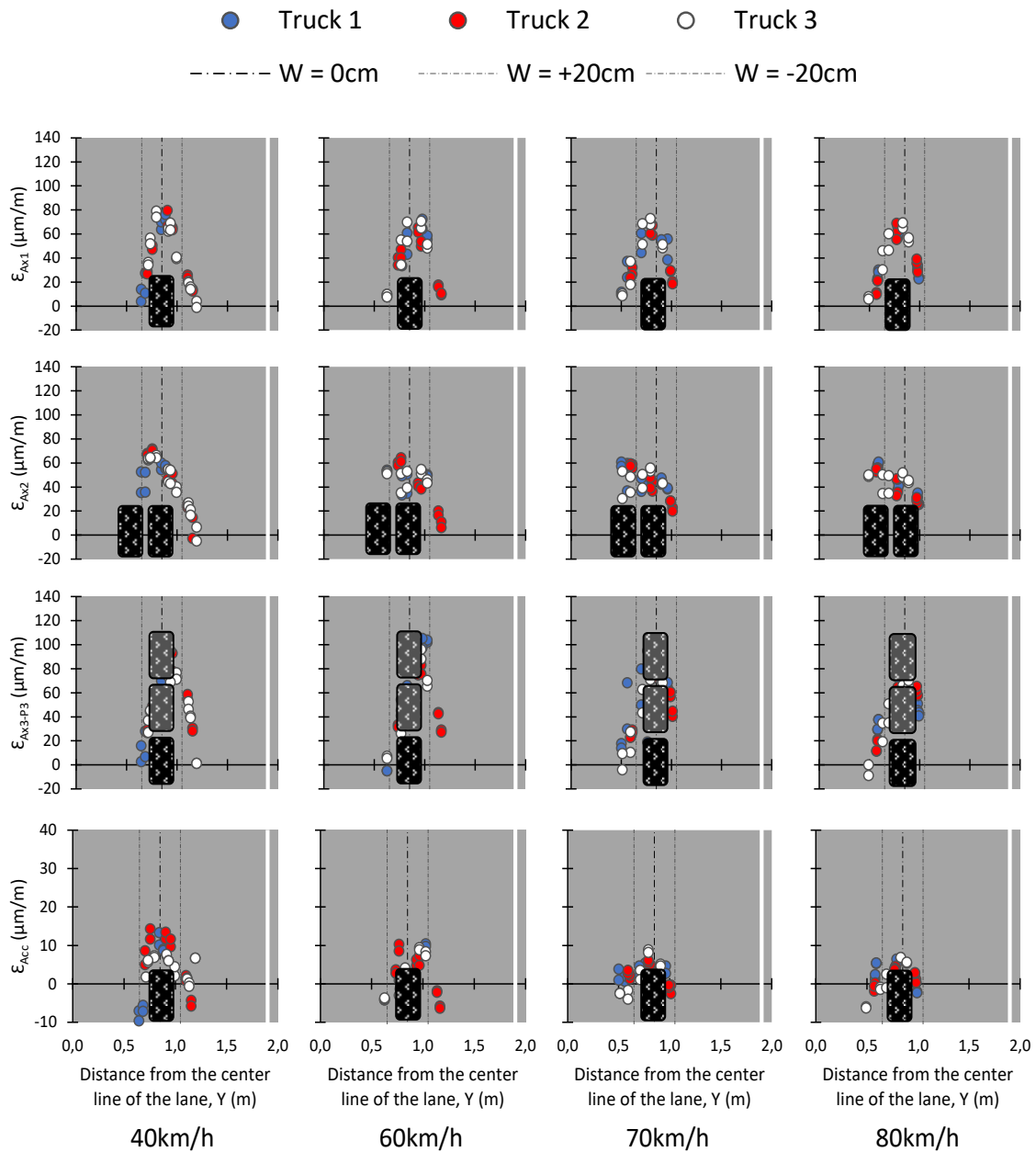


Fig. 20. Transversal strains at the points of analysis for individual configuration (summer campaign).

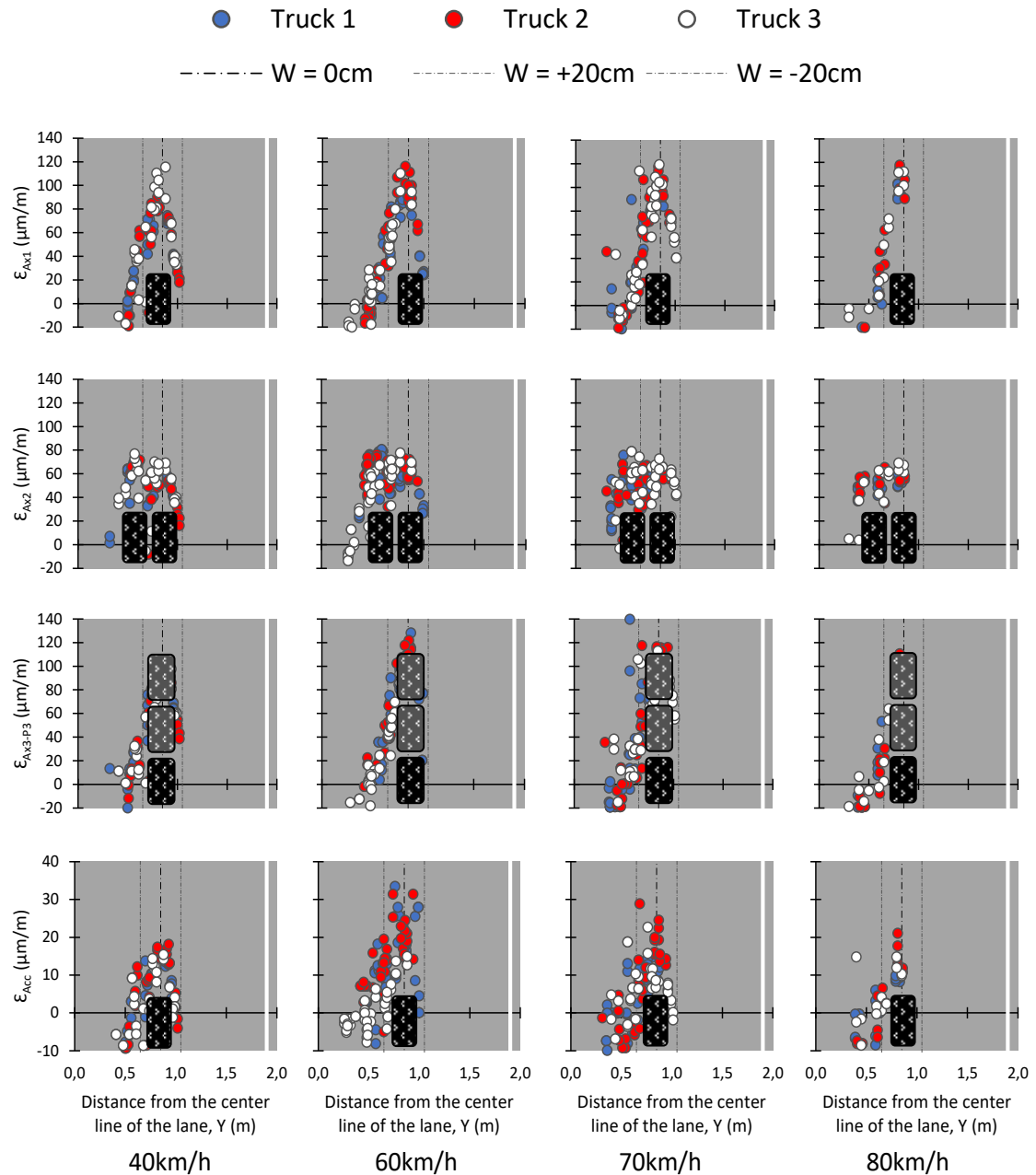


Fig. 21. Transversal strains at the points of analysis for the platoon configuration (summer campaign).

### 3.4.2. Data comparison and statistical analysis for the critical strain levels

With the purpose to compare the effect of individual trucks and platoon configurations, Fig. 22 and Fig. 23 show the average strain values obtained from both winter and summer test campaigns, by selecting only runs with a lateral deviation of  $\pm 15$  cm from the strain gauge, i.e. a wandering of  $\pm 15$  cm. Fig. 24 shows the percentage of increase of strains

between the winter and summer campaign, for individual trucks, and for platoons. The results indicate that:

- The critical strain values under Axle 1 and Axle 2 have similar values; The strains produced by Axle 3 are approximately 20% higher, for both test campaigns.
- Compared with the individual configuration, platoon configurations lead to an increase of strain levels only in the summer campaign. The inter-truck distances also affect the summer results. Here it is important to note that for the winter campaign, the slight reduction in strain values obtained for the platoons can be result of the temperature conditions during testing, which were a little lower in this case.
- The percentage of change obtained from comparing the strain values associated to each strain level, reveals big increases for the summer campaign in comparison to the winter one. The effect is even more noticed for the accumulated strain values.

The Multivariable Analysis of Variance (MANOVA) (Montgomery and Runger 1994) of this data helps to support the previous comments, since it is concluded that for a confidence level of 95% and the winter campaign, the strain values do not change by varying the (1) the load configuration, (2) the truck speed, and (3) the truck number, while in the summer campaign the variations of all these parameters change the strain values. Therefore, in order to identify the conditions producing differences for the summer campaign, the Tukey's honest significance tests for a confidence level of 95% revealed that:

- In relation to the axle number, the average strains obtained under the passage of Axle 1 and Axle 2 are significantly the same and differ from the ones obtained under the passage of Axle 3, which are around 20% higher.

- In relation to the truck speed, the values differ for all the cases between the individual and platoon configuration, except for the speed of 40 km/h, where the difference is not significant.
- In relation to the truck number, the strain values are the same for all the conditions, except for the accumulated strain.

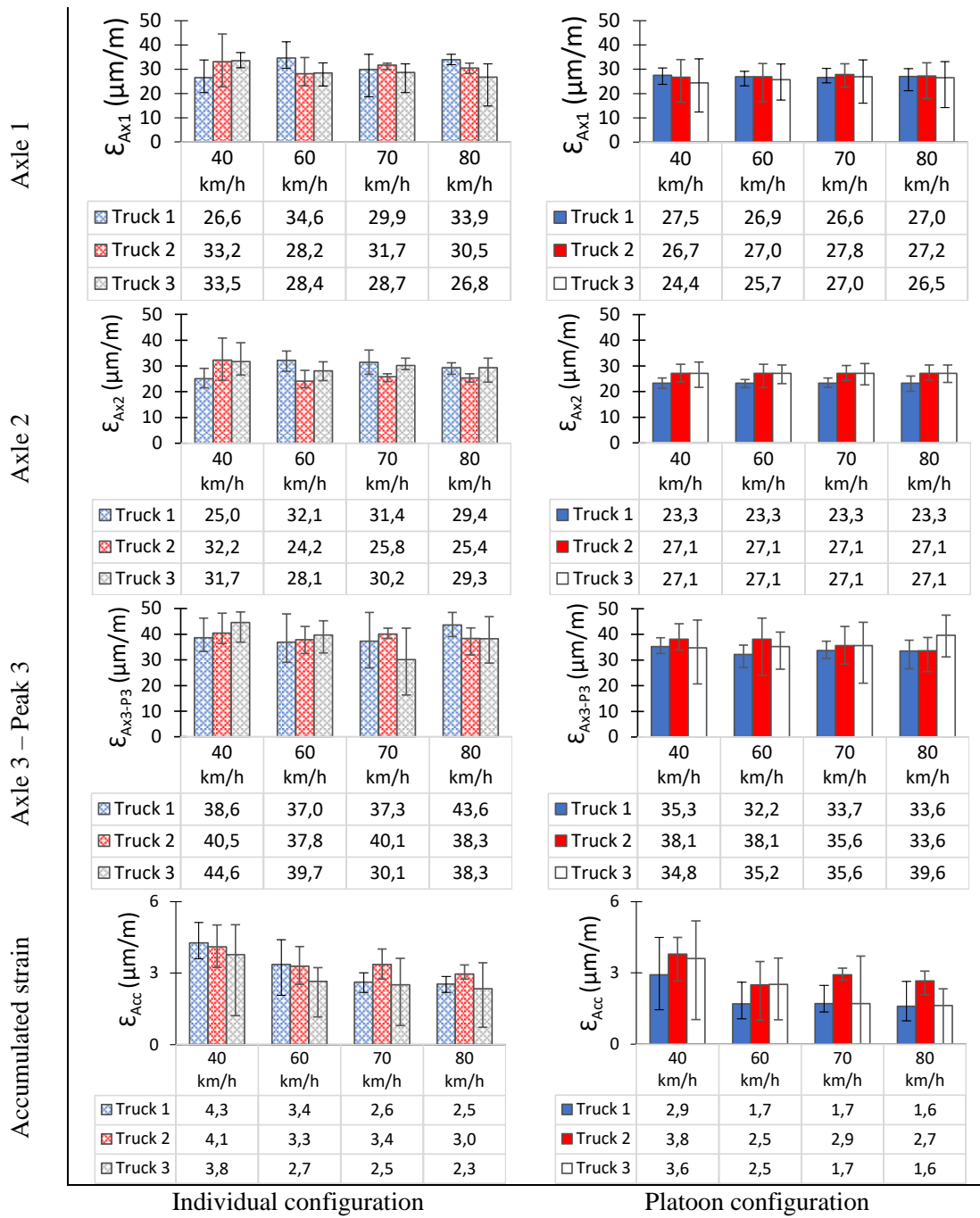


Fig. 22. Comparison of the strains at the different points of analysis for the individual and platoon configuration, when wandering is limited to 30 cm, in the winter campaign.

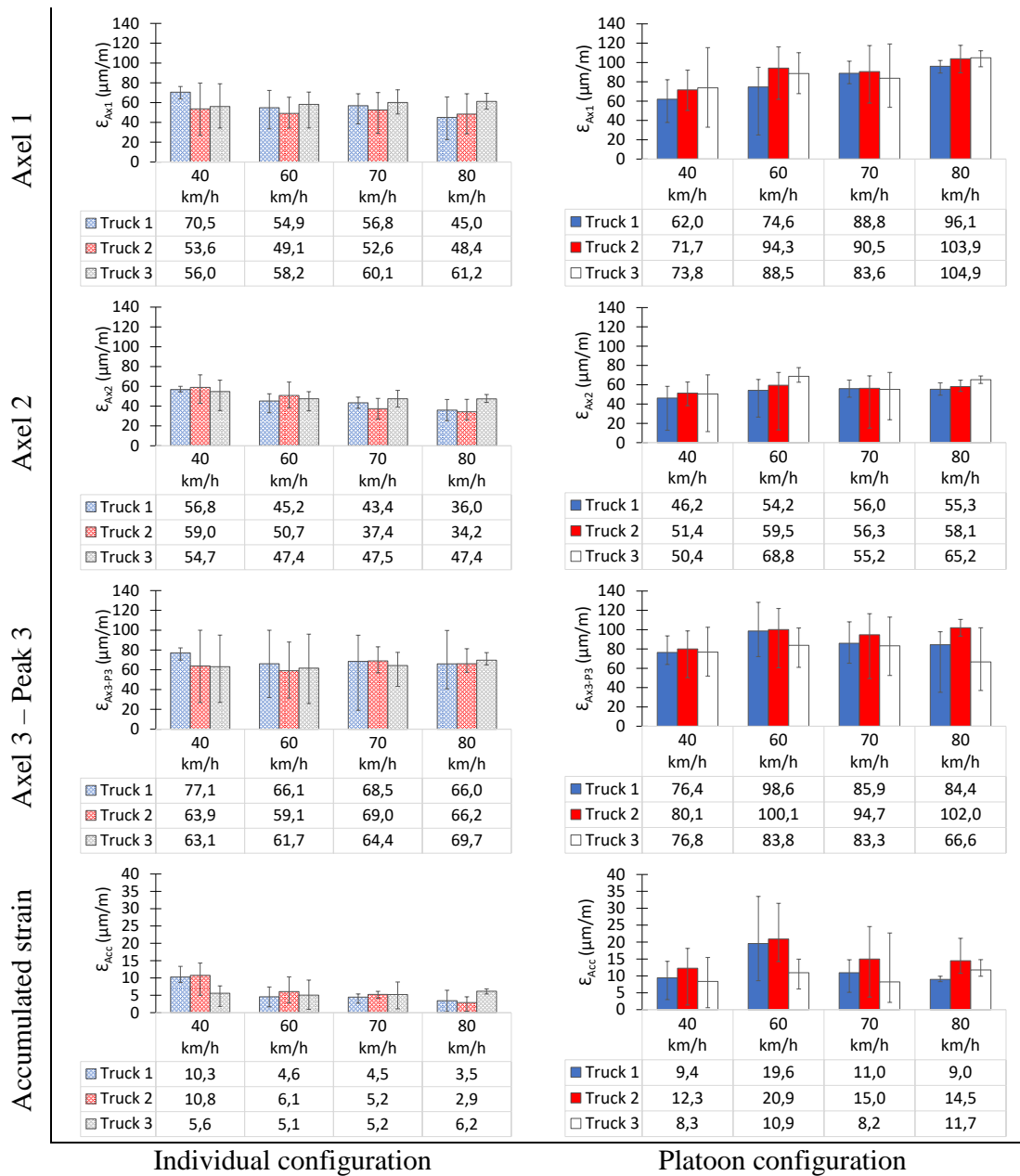


Fig. 23. Comparison of the strains at the different points of analysis for the individual and platoon configuration when wandering is limited to 30 cm, in the summer campaign.

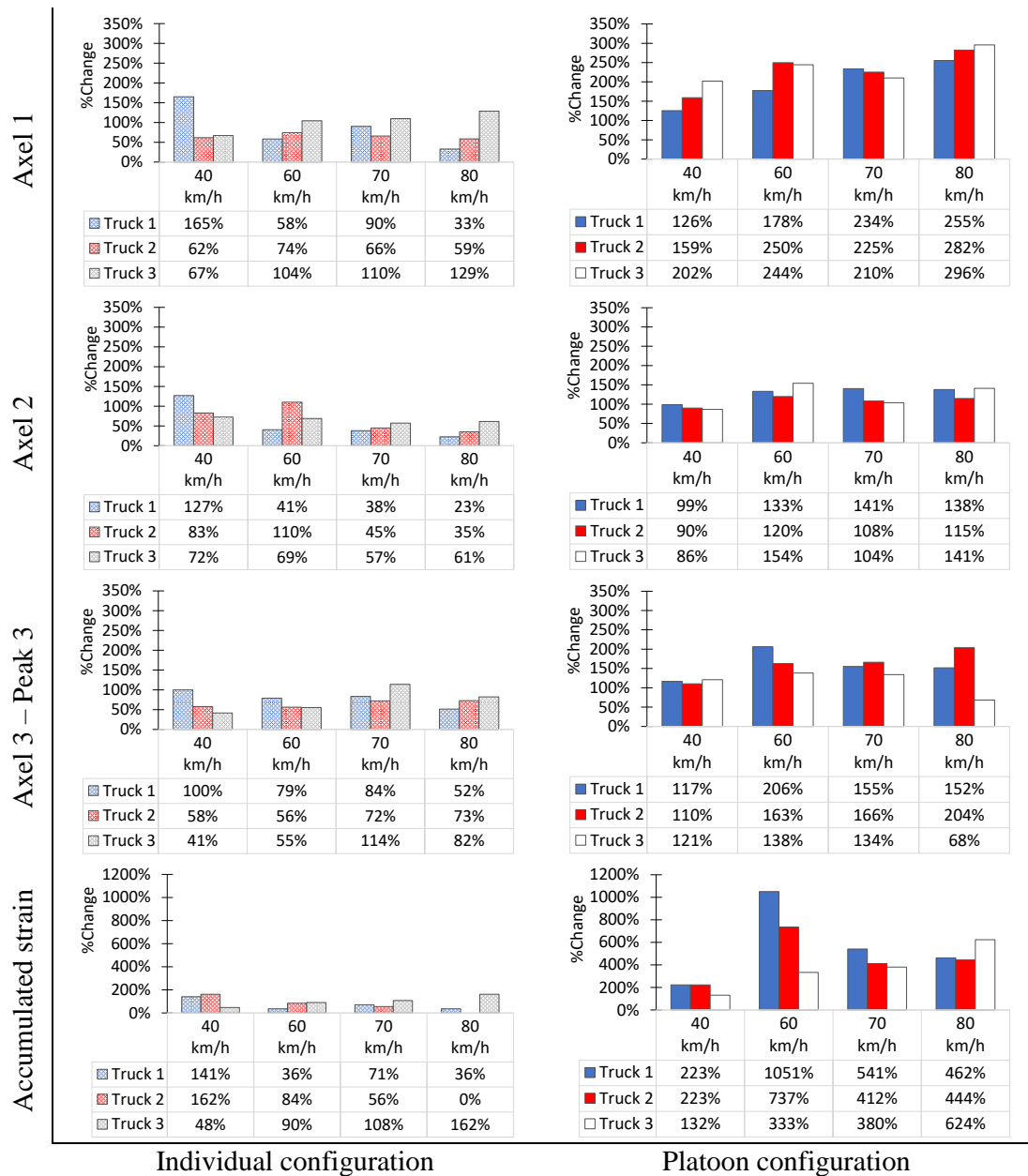


Fig. 24. Strain increase (in percentage) for each point of analysis comparing winter and summer campaigns

### 3.4.3. Effect of an increased wandering for the summer campaign

Considering the significant influence of platoon configurations in the summer campaign, Fig. 25 shows the average strain values obtained by including all truck passages with a wandering interval of  $[-25\text{cm}, +25\text{cm}]$  from the strain gauge, as well as the percentages of change in reference to the original wandering interval. As can be observed, the

extension of the wandering interval leads, in average, to a reduction of 20% of all the critical strain levels, except for Axle 2, for which the reduction is lower, due to its dual wheel configuration.

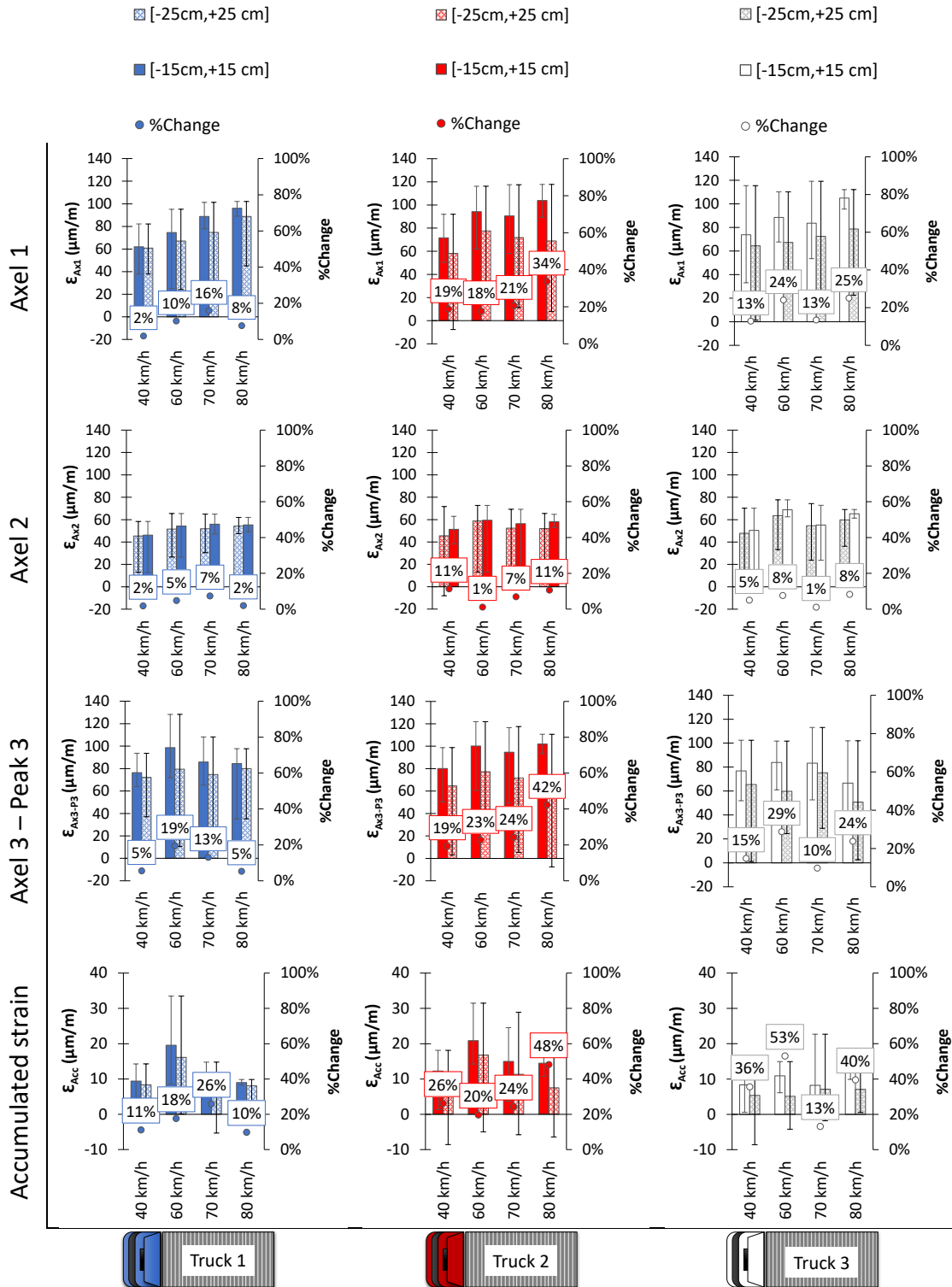


Fig. 25. Effect produced by the extension of the wandering for the summer campaign.



#### **4. Conclusions**

This study presents an analysis of the horizontal strains induced in the asphalt layers of a pavement test section subjected to the passage of trucks in individual and platoon configurations. The objective of the study was limited to evaluate the impact of the passage of trucks in platoon mode, over the fatigue strain values obtained from an instrumented pavement section located in the test track facilities of Applus IDIADA, in Tarragona, Spain. Fatigue life predictions associated with this research project will be complementary addressed in further research documents related to this research line. The test protocol used for this study included the following configuration:

- two loading scenarios, trucks travelling in individual and platoon configurations;
- two test campaigns, the first in winter and the second in summer;
- for each campaign, different test speeds and lateral deviations of the trucks from the strain gauges (wandering).

From the results obtained, the following conclusions can be drawn:

- The instrumentation designed and placed on-site allows collecting data with good reproducibility and repeatability. The data collected by each sensor were of good quality, and there was no loss of sensors during the construction process of the test section on IDIADA facilities.
- The agreement between the test speeds and the inter-truck distances measured from the instrumentation and the laser system, as well as its good homogeneity and consistency, proved that the defined test protocol allowed an adequate reproduction of platoon truck configurations.
- Although there were slight temperature variations during both individual and platoon configuration tests for each test campaign, the values were significantly

enough comparable. The inspection and statistical comparison of the strain values associated with the critical strain levels indicated that:

- There is not considerable effect of using platoon truck configurations during the winter campaign, due to the predominantly elastic performance of the material at low temperatures.
- The passage of trucks in platoon configuration during the summer campaign considerably affects the fatigue strain as result of a mostly viscoelastic behavior of the asphalt layers at the higher temperatures present during summer.
- The accumulated strain values were not considerably affected during the winter campaign due to the mostly elastic performance of the asphalt materials in the surface layers. The contrary situation happened during the summer campaign showing that the accumulated strain values were significantly different between individual and platoon configurations due to the thermo-viscoelastic performance of the materials in the asphalt layers.
- Extending the interval of lateral wheel wandering from [-15cm, +15cm] to [-25cm, +25cm] could reduce the average critical tensile strain values in the pavement structure. This means that a small increase in the wandering among the trucks in platoon mode can significantly reduce the fatigue damage of the pavement, distributing the highest tensile strains over a larger area.

In summary, the study has proved that the effect of Platoon Configurations could be potentially reduced by means of: (1) the management of their distribution along the year and along the day, with a preference for highest transit rates during the winter months or

for further research, avoiding the warmest hours during the day (2) the increase of the lateral wandering between the trucks inside the platoon, as well as between platoons, particularly when the temperatures are high. , and (3) for further research, the increase in the inter-truck distances, especially during the summer season. In reference to previous studies, based mostly on modeling with damage predictions, traffic modeling and some real scale testing (Chen et al. 2019, 2020; Gungor et al. 2020; Gungor and Al-Qadi 2020a, 2020b; Hoque et al. 2021; Marsac et al. 2020; H. Noorvand et al. 2017; Rana and Hossain 2021; Song et al. 2021; Zhou et al. 2019) this proper management could be reflected in terms of: (1) longer fatigue cracking/permanent deformation life, (2) lower pavement structure design thicknesses and (3) later rehabilitation/maintenance treatments.

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