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1. EXECUTIVE SUMMARY

1.1. Context and need of a multi brand platooning project

Context

Platooning technology has made significant advances in the last decade, but to achieve the next step towards deployment of truck platooning, an integral multi-brand approach is required. Aiming for Europe-wide deployment of platooning, 'multi-brand' solutions are paramount. It is the ambition of ENSEMBLE to realise pre-standards for interoperability between trucks, platoons and logistics solution providers, to speed up actual market pick-up of (sub)system development and implementation and to enable harmonisation of legal frameworks in the member states.

Project scope

The main goal of the ENSEMBLE project is to pave the way for the adoption of multi-brand truck platooning in Europe to improve fuel economy, traffic safety and throughput. This has been demonstrated by driving up to seven differently branded trucks in one (or more) platoon(s) under real world traffic conditions across national borders. During the years, the project goals were:

- Year 1: setting the specifications and developing a reference design;
- Year 2 and 3: implementing this reference design on the OEM own trucks, as well as performing impact assessments with several criteria;
- Year 4: focus on testing the multi-brand platoons on test tracks and public road.

The technical results will be evaluated against the initial requirements. Also, the impact on fuel consumption, drivers and other road users was established. In the end, all activities within the project aim to accelerate the deployment of multi-brand truck platooning in Europe.

Abstract of this Deliverable

Deliverable D4.1 deals with the assessment of the impact of multi-brand platooning on road infrastructure, namely pavements, bridges and tunnels.

The impact on pavements has been assessed through experimental and numerical works. The impact on tunnels has been assessed through the answers to a questionnaire sent to tunnels operators. The impact on bridges has been evaluated using numerical modelling and calculations tools.

The impact of platoon on bridges can be summarized by the consequences of (1) more loading on bridges, (2) loadings localized at a given lateral position on the lane, and (3) more and closer horizontal forces.

The three consequences have been investigated within this work: it has been shown that while the effects of platoons stay below those of the European bridge loading models, a non-negligible increase in aggressivity of the traffic is observed. Moreover, platoons driving in the same lateral position leads to increased damage on some types of bridges, and therefore a dissolving (or higher gap) of the platoon might be profitable. To finish, horizontal forces and in particular braking forces for platoons need to be checked seriously, contrary to what might be done nowadays when reassessing existing bridges.

The impact on tunnels has been assessed through the answers to a questionnaire sent to tunnels operators.

The PIARC committee for tunnels has accepted to consider this questionnaire, and several of its members have sent in their answers. The answers have shown a diversified situation, in terms of tunnels (geometry, current traffic situation and management) and of behaviour towards (future) autonomous traffic. In particular, while a few tunnels operators have realized detailed studies on the impact of autonomous driving or have introduced new connectivity technologies to enable or test new types of mobility, most of them are still focused on the “traditional” traffic, with traditional traffic management measures.

To finish, whereas the dangers and the drawbacks associated with platoons seem to be well known by tunnel managers, it seems that the opportunities brought by autonomous – connected – digitalized driving, and its associated data sharing, are not recognized. Explanations about the possibilities should be sought, demonstrated and explained. The associated business models and case values should be studied for various types of traffic situations in tunnels.

2. INTRODUCTION

2.1. Background

Road infrastructure is designed to last many years, bridges and tunnels for over 100 years and pavements for 15-20 years. Moreover, the design load models and design procedures are developed and updated in a non-frequent way: the Eurocodes (design codes for bridges) have been developed in the 1980s, and only now a revised version of the Eurocodes is being discussed. On the other side, during this period, traffic has changed a lot (X. Y. Zhou et al., 2012).

This difference in timeline between infrastructure and traffic shows the need for anticipation of future traffic loads and future wear/damage expectations.

2.1.1. Platooning trucks: a new type of load for pavements

From the point of view of pavement engineering, platooning trucks represent a new type of loads for pavement structures. As shown in Figure 1, this new type of loads is characterised by:

1. multiple loads generated by the multi-axle configurations of the trucks forming the platoon,
2. traffic channelization due to the reduced lateral wandering of the trucks in the platoon and between platoons,
3. reduced inter-truck time gaps, which may reduce the self-recovery capacity of asphalt concrete materials, reducing the pavement service life.

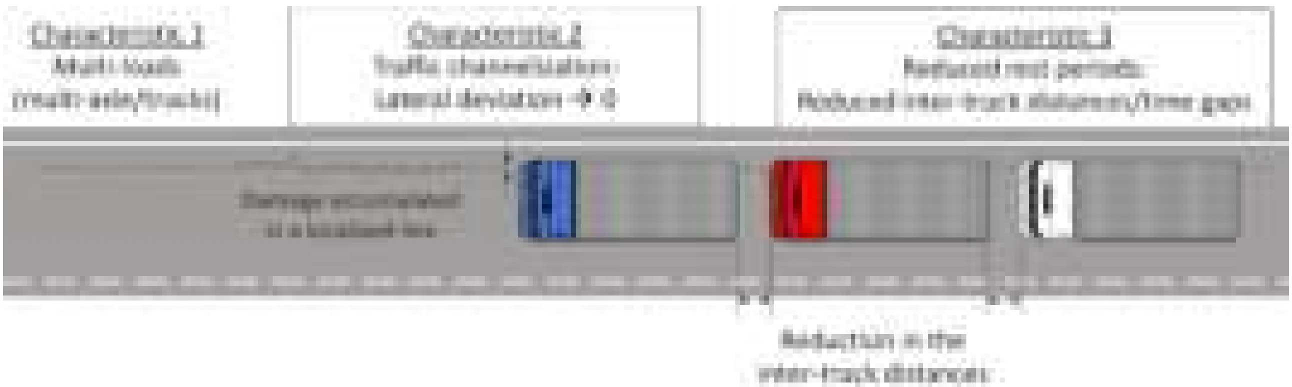


Figure 1. Characteristics associated with platooning trucks and their effect in pavement structures.

As shown in Table 1, the effects of parameters such as wandering, platoon penetration, lateral offset, inter-truck distances, vehicle number and traffic distribution, which are associated with these characteristics, have been analysed in recent studies mainly focused on numerical modelling. According to these studies, the lack of control of these parameters for platooning trucks could result in higher pavement rutting or fatigue damage, leading to an increase of associated construction and maintenance costs.

Ref Country Type of study	Parameter	Conditions evaluated	Findings related to pavement variables (rutting, fatigue, sustainability, costs)
(Noorvand et al., 2017) Country: United States. Type of study: Modelling (mechanistic-empirical evaluation).	Wandering	Vehicle distribution: (1) normally distributed non-autonomous trucks (standard deviation of 25 cm), (2) zero wander autonomous trucks, (3) uniformly distributed autonomous trucks (125 cm width in the path way of each tire).	In terms of rutting and fatigue damage: - For a uniform distribution of wandering: the pass of an autonomous truck is equivalent to 0.65 (rutting) and 0.81 (fatigue) passes of a non-autonomous truck.This means that including a uniform distribution of wandering 125 cm width could reduce the rutting and fatigue damage associated to platooning trucks with zero wandering for the case of study analysed.
	Platoon penetration	Scenarios: Scenario 1 (Reference): Only non-autonomous vehicles. Scenario 2 (Integrated): Autonomous and non-autonomous in the same lane. Scenario 3 (Segregated): Autonomous and non-autonomous in different lane.	
(Chen et al., 2019, 2020). Country: China Type of study: Modelling (finite element).	Wandering	Lateral control modes: (1) zero-wander mode, (2) uniform mode, (3) double peak Gaussian mode and (4) two-section uniform mode.	Including lateral control modes can: - Delay maintenance treatments addressed to treat rutting by 2.3 years. - Reduce fatigue damage by up to 35 % in reference to a zero-wander distribution.
(Song et al., 2021) Country: China Type of study: Modelling (finite elements and fluid dynamics simulations).	Lateral offset (for each truck in the platoon)	Scenarios (two trucks): (1) without lateral offset, (2) Current lanes: 0.21 m, 0.42 m, 0.63 m, 0.84 m and 1.05 m. (3) Wider lane in the future: 1,26 m, 1,47 m and 1,68 m.	Lateral offset recommended values (two trucks, 0.5L): between 100 mm and 150 mm for a fuel saving rate of 8% and fatigue damage reduction above 30%. This interval is based on the longitudinal tensile strain under the wheels loads in the transversal view for a typical wheel load (standard wheel load used for pavement design: 100 kN, single axle, dual-tire load, tire stress = 700kPa).
	Vehicle number	2 to 6 trucks (inter-truck distance = 0.5L).	
	Longitudinal interval (inter-truck distances)	0.5L, L, 1.5L, 2L, 2.5L, 4L and 5L. L: length of a single truck = 12 m.	
(F. Zhou et al., 2019) Country: United States. Type of study: Experimental (Autonomous Vehicle facilities of the Texas A&M University). Modelling (mechanistic-empirical evaluation).	Lateral wandering patterns	Lateral wandering pattern obtained from measurements of platoons and human driven vehicles travelling at 80, 96 km/h and 112 km/h : - Normal distribution with a standard deviation. - Platoon standard deviation = 30 to 75 mm. - Human driven standard deviation = 250 mm. → Lateral deviation of platoon three times smaller than for human driven trucks	AV can: Shorten pavement fatigue life by 20%. Pavement rut depths (RD) increase by 13% and reach critical values 30% earlier. Higher RD increase water film on the surface and risk of hydroplaning. A uniform lateral wandering pattern can prolong pavement fatigue life, reduces pavement RD and decreases hydroplaning potential.
	Traffic (Fixed values for this study)	Scenarios: - 100% human driven vehicles. - 100% platoons.	
	Truck weights (Fixed values for this study)	Heavy load (not specified). Tire inflation pressure = 690 kPa.	
(Gungor et al., 2020; Gungor & Al-Qadi, 2020b, 2020a). Country: United States. Type of study: Modelling (statistics and	Wheel wandering (lateral position)	Software Wander 2D (a damage profile shifted laterally - uncertainty of this profile -): - human driven: random values that follow certain distribution. - autonomous trucks: can be probabilistic (a random variable with less uncertainty than for human driven trucks) or a deterministic value.	Controlling the platoon lateral position can generate a reduction in the pavement-lifecycle costs of up to 50% The reduced time between two consecutive vehicles can hinder the self-healing mechanisms of asphalt concrete (AC) and consequently reduce the pavement's service life. Platoon control strategies proposed (lateral position of trucks and inter-vehicle spacing for
	Inter-truck time gaps (rest periods).	Inter-truck distances in platoon: 3 to 10 m. Inter-truck distances in human driven trucks: 60 to 90 m.	

applied mathematics to improve MEDPG inputs).			a specific number of trucks) could reduce costs to agencies and users by 9%: Centralised optimisation: lateral positions of platoons are optimised. Decentralised optimisation: optimising the lateral position of each truck in a single platoon.
(Rana & Hossain, 2021) Country: Canada. Type of study: Modelling (mechanistic-empirical analysis).	Wandering	Distribution patterns: (1) zero wander, (2) normal distribution with standard deviation = 7.5 cm, (3) normal distribution with standard deviation = 25 cm, (4) uniform distribution.	Significant reduction in the pavement distress when: - the wheel wander is increased, - the traffic distribution in the road lanes is uniformly and equally distributed, and - the passages are mainly assigned to the low-temperature period of the day. These parameters may reduce asphalt concrete rutting and cracking by 23.9 % and 30.7 % respectively, preventing early deterioration of the pavements.
	Traffic distribution.	Three scenarios (based on dedicated lane for autonomous trucks and sharing lane for autonomous and non-autonomous): (1) baseline (only non-autonomous), (2) separated (dedicated lane for autonomous trucks), (3) integrated (a single lane is shared by autonomous and non-autonomous trucks).	

Table 1: Summary of research studies on the impacts of platooning on pavement structures.

2.1.2. Platooning trucks: a new type of load for bridges

In Europe, bridges are currently design according to the Eurocodes. In particular, the design of bridges to traffic loads is regulated in Eurocode 1 part 2 (CEN, 2003) which are European regulations, which national annexes which adapt this framework to given countries (as (NF-EN-1992-2, 2008) for example in France).

The bridge design is then based on load models, which are applied on the bridge to be designed to check the acceptability of the encountered stress and displacements. There are 5 of these loads models, among which LM1 ("Load Model1") is the most well-known and generally applied for highways, and LM5 gives the possibility to use recorded traffic files for bridge design

These load models have been calibrated in the 1990s, based on traffic files measured in Europe at the end of the 1980s. Since then, the traffic has become denser and heavier: the safety margins have been decreased (X. Zhou et al., 2016). It is to be expected that with the introduction of platoons, the aggressivity of traffic might increase, when comparing the effects in bridges of platoons with the ones of the traffic loads as authorized by Directive 96/53/EC (The Council of the European Union, 1996) and Directive 2015/719 (The European Parliament and the Council, 2015).

The structural issues to be checked with the introduction of platoons are the closer vertical loads, the laterally aligned loadings, and the closer horizontal loads. These three points are described below.

2.1.3. Platooning trucks: a new type of load for tunnels

After assessing the impact of multi brand platooning on pavement and bridges, this task 4.1 goes on with assessing the impact on tunnels, or more precisely the opportunities and the hurdles of this type of semi-autonomous driving in tunnels.

For bridges and tunnels, the work has mainly focused on the physical impact of platooning, by assessing experimentally and calculating the wear caused by platoons, compared to current traffic. This has shown that the parameters that describe the platoon (number of trucks, loading of trucks, longitudinal gap, lateral positioning in lane) are very important, and can be the opportunity for the road operator to better manage the heavy traffic. In particular, the need for the road authorities to obtain precise, real-time information on the traffic has been shown.

As far as tunnels are concerned, the methodology will be different. Indeed, the initial finding is different: as already stated previously (Franziska Schmidt, 2017), (Franziska Schmidt, 2018), the physical infrastructure itself will not be affected by this new type of freight transport, but safety issues might arise.

2.2. Structure of this report

This report begins by explaining the methodology and the results about the assessment of multi brand platooning on pavements. Afterwards, the impact on bridges will be explained. To finish, the impact of multi brand platooning on tunnels will be described by detailing and explaining the answers of tunnel operators to the questionnaire about their view about automated traffic and other connected, new types of mobility.

3. SUBTASK 4.1.1. IMPACT OF PLATOONS ON PAVEMENTS

Bearing in mind the importance of achieving an integrated deployment of platoons, ENSEMBLE Subtask 4.1.1. Impact of platoons on pavements defined the research plan shown in Figure 2.

This research plan is based on the elaboration of three main tasks: (1) the experimental evaluation of the effect of truck platooning on a full-scale pavement structure, (2) the experimental definition of a new fatigue law for flexible pavements, and (3) the validation of a numerical model for the analysis of different platooning truck configurations on pavement structures.

These three main tasks aimed to provide tools to help transport policymakers understand the impact of platoons on pavement structures and propose solutions to limit it.

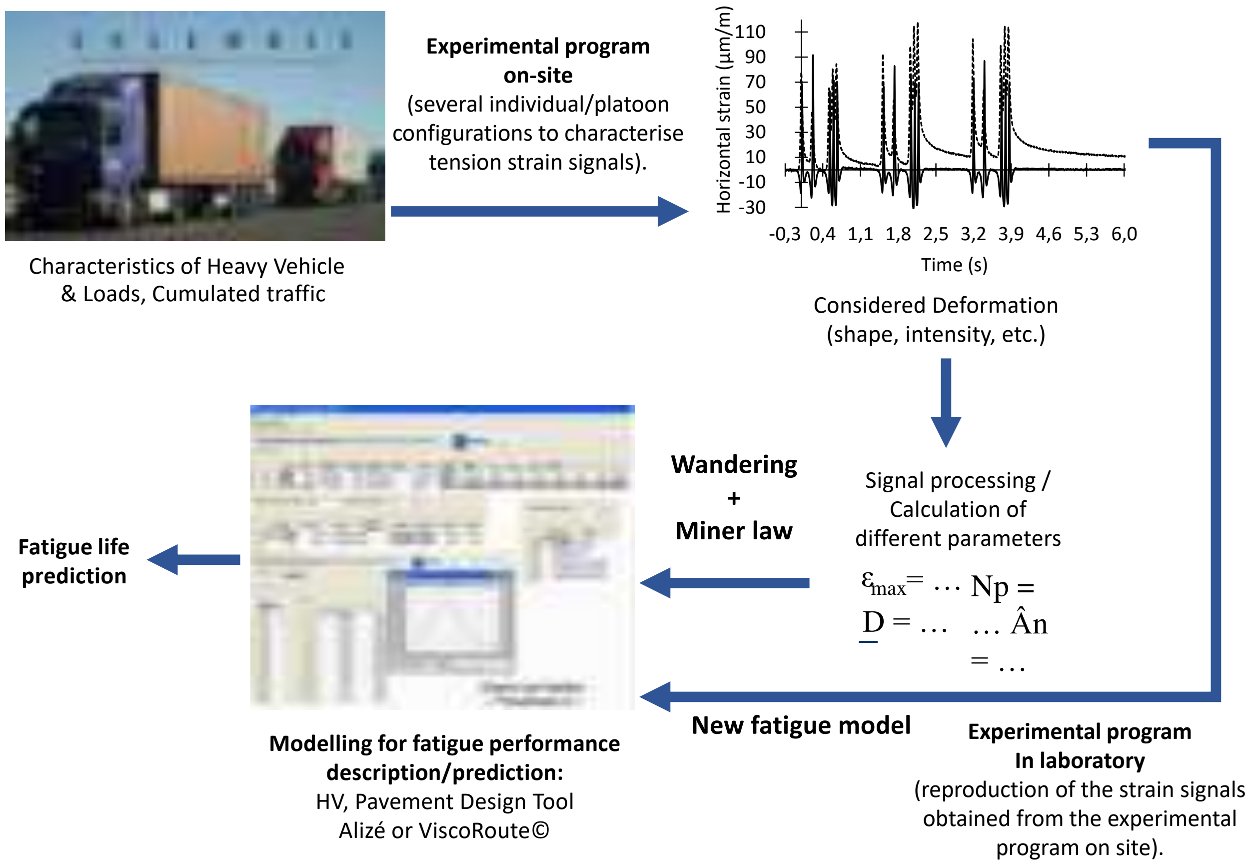


Figure 2: Research plan for Subtask 4.1.1 Impact of platoons on pavements.

3.1. Experimental program: test on-site

3.1.1. Pavement test section

The test section analysed in this study is located in the test track facilities of Applus IDIADA, located in Tarragona, Spain, 70 km from Barcelona. This test track facility has been operating since 1994 and is composed of 370 hectares of land. The primary services provided by this test track are related to providing design, testing, engineering and homologation services to the world's leading vehicle manufacturers. Their climate conditions allow year-round testing plans to be executed for the automotive sector.

As shown in Figure 3, the experimental campaign performed in Subtask 4.1.1 used the sections highlighted in light blue, red and green. The light blue section was required for trucks to stabilise test speeds, lateral deviation and inter-truck time gaps. The red section is the one under testing. And finally, the green one, the return trajectory for the trucks.

Figure 3: Applus IDIADA test track facilities and Ensemble test section

3.1.2. Pavement structure and instrumentation.

The test section under study consists of three asphalt layers (a wearing course, a binder course and a base course) placed over a granular foundation with a continuous grading curve (type zahorra by the Spanish acronym). As shown in

Layer	Thickness (cm)	Material type	Asphalt binder	Density (g/cm^3)	Air voids (%)
Wearing course	4	AC11 surf (D12) *	PMB 45-80/65	2.39	4.7
Binder course	6	AC 22 S (S-20) *		2.38	5.8
Base layer	15	AC 22 G (G-20) *		2.38	6.8
Foundation (granular base)	-	Granular material with continuous granulometry (type zahorra)	-	-	-

Notes: * Classification according to UNE-EN 13108-1 and UNE-EN 14023.

Table 2, the surface layers are composed of asphalt concrete (AC) mixtures with 11 and 22 mm maximum aggregate sizes, and dense (D), semi-dense (S), and coarse-grained (G) granulometry. The binder used is a polymer modified bitumen (PMB) with a softening point over 65 °C and penetration grade between 45 and 80 1/10 mm.

Layer	Thickness (cm)	Material type	Asphalt binder	Density (g/cm^3)	Air voids (%)
Wearing course	4	AC11 surf (D12) *	PMB 45-80/65	2.39	4.7
Binder course	6	AC 22 S (S-20) *		2.38	5.8
Base layer	15	AC 22 G (G-20) *		2.38	6.8
Foundation (granular base)	-	Granular material with continuous granulometry (type zahorra)	-	-	-

Notes: * Classification according to UNE-EN 13108-1 and UNE-EN 14023.

Table 2: General characteristics of the test track materials.

As shown in Figure 4, the test section is 12 m long, and was instrumented with 24 strain gauges of type KM-I00HAS Tokyo Sokki Kenkyujo (details shown in

Parameter	**Technical specifications**
Type	KM-100HAS
Capacity	±5000 x 10-6
Rated output	Approx. 2.5 mV/V
Non-linearity	1.0%RO
Apparent elastic modulus	Approx. 40 N/mm2
Temperature range	-20~ + 180 °C
Bridge excitation	Recommended 1 ~ 2 V, Allowable 10 V
Resistance	350 Ω full bridge (Strain measurement) Quarter bridge in 3-wire system (Temperature measurement)
Electrical connection	6 mm dia. 0.3 mm2 5-core shielded Fluoroplastic cable, 2 m long

Table 3 and Figure 5) placed at 10 cm and 25 depth from the pavement surface. Half of the strain gauges measured the strains in the longitudinal direction and the other half the transversal one.

The array used was configured to place the strain gauges at three distances from the border of the safety lane: 0.85 m, 1.05 m and 1.25 m. This instrumentation allows evaluating the strains in the pavement when trucks in individual and platoon configurations pass at several lateral positions.

The instrumentation placed also includes six thermocouples, placed at the bottom of each asphalt layer (wearing, binder and base course) at two different locations.

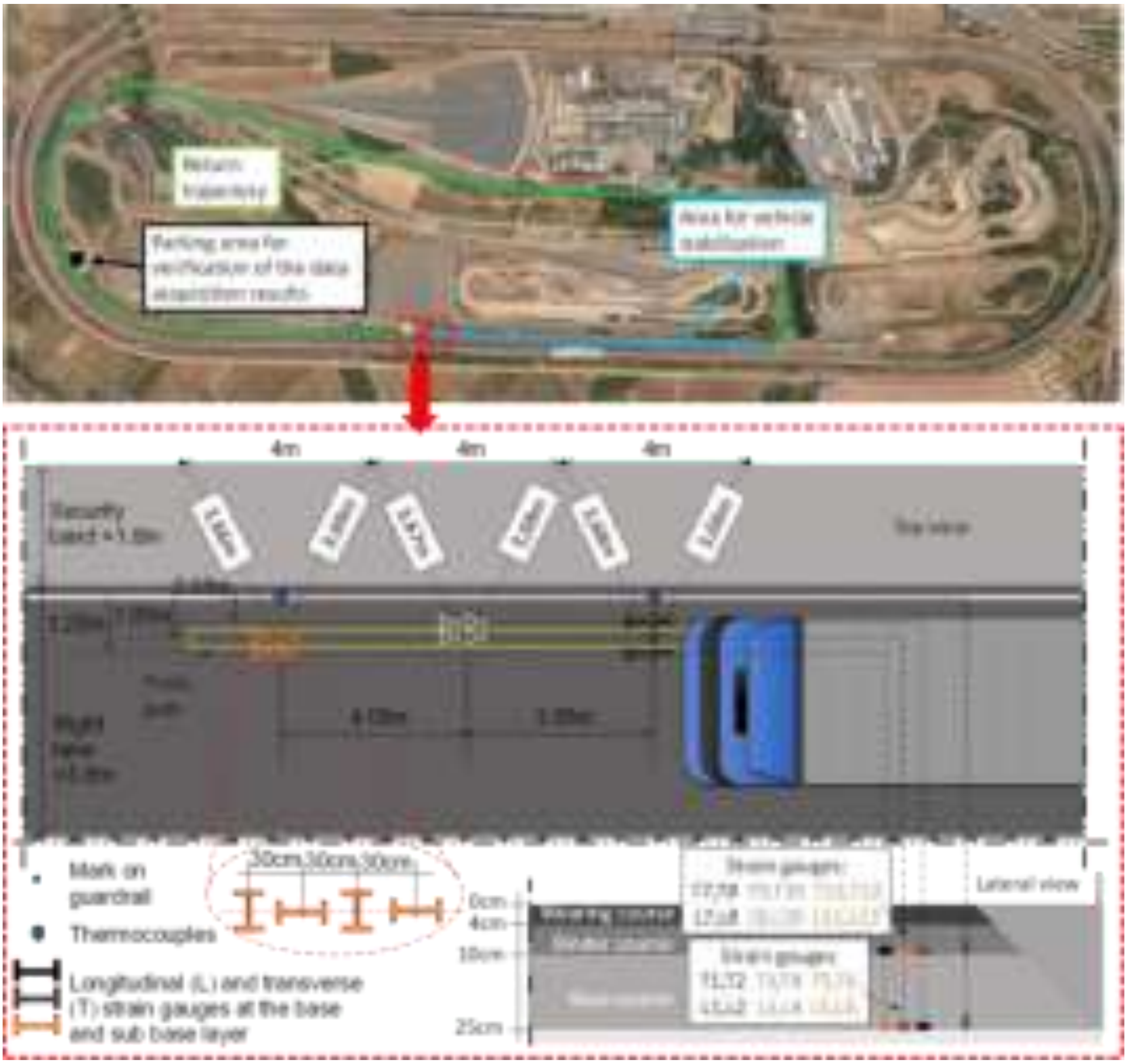


Figure 4: Details about the instrumentation installed on site.

Parameter	Technical specifications

Type	KM-100HAS
Capacity	±5000 x 10^{-6}
Rated output	Approx. 2.5 mV/V
Non-linearity	1.0%RO
Apparent elastic modulus	Approx. 40 N/mm^2
Temperature range	-20~ +180 °C
Bridge excitation	Recommended 1 ~ 2 V, Allowable 10 V
Resistance	350 Ω full bridge (Strain measurement) Quarter bridge in 3-wire system (Temperature measurement)
Electrical connection	6 mm dia. 0.3 mm^2 5-core shielded Fluoroplastic cable, 2 m long

Table 3: Strain gauges specifications.

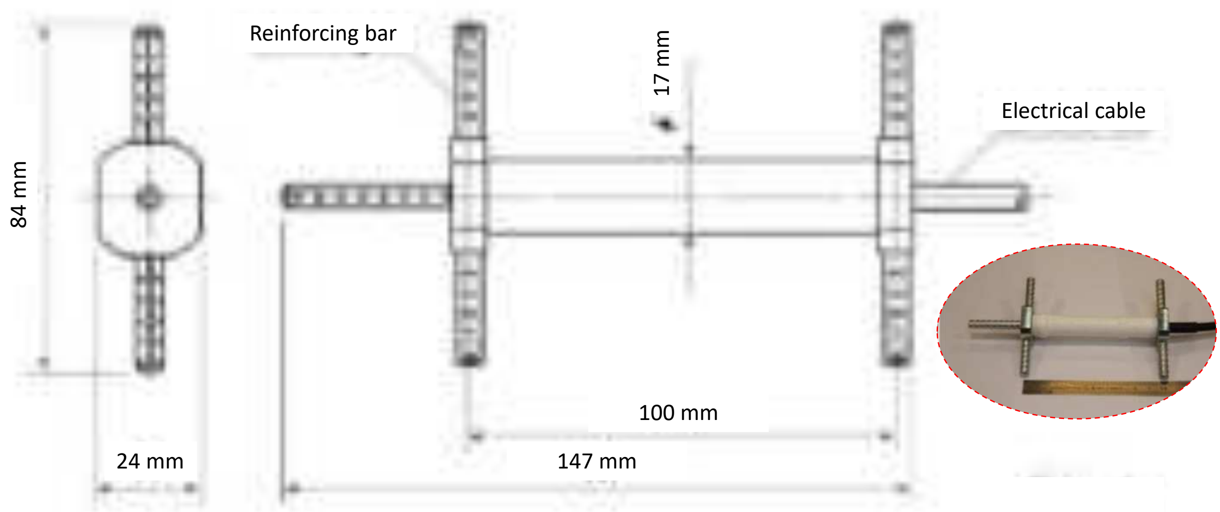


Figure 5: Strain gauges dimensions.

3.1.3. Construction process

The construction process associated with the installation of the instrumentation previously described was composed of the following eight steps:

Step 1: Surface layers (wearing course, binder course and base course) milling.

Step 2: Cleaning of the milled surface and tack coat application (Figure 6).

Step 3: Placement of 2 thermocouples separated by a distance of 8 m and the first set of strain gauges (6 to measure in the transversal direction and 6 in the longitudinal.

Step 4: Placement of a 15 cm thick bituminous base course.

Step 5: Place the second set of strain gauges (6 to measure in the transversal direction and 6 in the longitudinal) and two thermocouples more.

Step 6: Placement of a 6 cm thick bituminous binder course.

Step 7: Placement of the last 2 thermocouples.

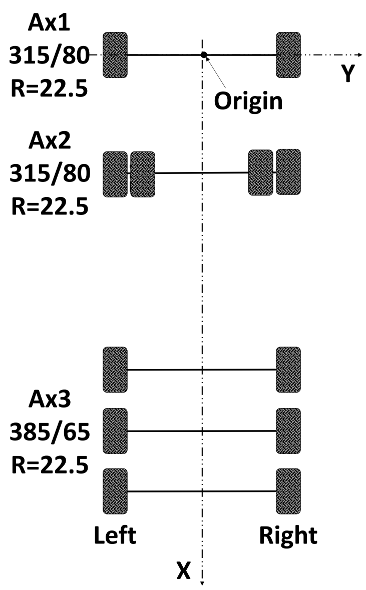
Step 8: Placement of a 4 cm thick bituminous wearing course.

Figure 6: Instrumentation during the construction process.

3.1.4. Truck characteristics

As shown in Figure 7, the trucks used in the study were five-axle semi-trailer trucks (with a steer axle, a dual wheel drive axle and a tridem trailer axle) loaded at their maximum legal load of 40 tons. Figure 8 shows the details of the geometrical configuration, loads per axle and type of tires for each truck.

Figure 7: Trucks used during testing.



Truck	Axle	Tyre	Y (m)	X (m)	Winter campaign Load (kN)		Summer campaign Load (kN)	
					Left	Right	Left	Right
Truck 1	Ax1 (Steer)	Tyre 1	1.0735	0.0	34	34	36	34
	Ax2 (Driven)	Tyre 1+2	1.0735 0.7205	3.7	59	61	54	50
	Ax3 (Trailer tridem)	Tyre 1	1.0575	5.7	42	43	33	40
		Tyre 2	1.0575	7.1	41	40	38	36
		Tyre 3	1.0575	8.4	32	31	39	34
Truck 2	Ax1 (Steer)	Tyre 1	1.0735	0.0	34	34	42	40
	Ax2 (Driven)	Tyre 1+2	1.0735 0.7205	3.7	59	58	61	58
	Ax3 (Trailer tridem)	Tyre 1	1.0575	9.5	39	39	31	42
		Tyre 2	1.0575	10.8	38	39	30	32
		Tyre 3	1.0575	12.1	36	40	55	41
Truck 3	Ax1 (Steer)	Tyre 1	1.0735	0.0	33	35	41	38
	Ax2 (Driven)	Tyre 1+2	1.0735 0.7205	3.7	61	63	58	58
	Ax3 (Trailer tridem)	Tyre 1	1.0575	9.3	37	35	19	25
		Tyre 2	1.0575	10.6	38	35	36	37
		Tyre 3	1.0575	11.9	36	36	55	46

Figure 8: Axle geometrical configuration and weight of each truck.
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

3.1.5. Test protocol

As shown in Figure 9, two loading cases were applied during the experiment: trucks passing individually and forming a platoon. Since the experiment was performed at the beginning of the ENSEMBLE project, three human driven trucks simulating individual and platoon truck configurations were used in the experiment.

Therefore, as shown in Figure 10, a laser system composed of 4 lasers was used to evaluate the positioning of the individual and platoon truck configurations required in the experiment (i.e. specific truck speeds and reduced wandering for both cases and reduced inter-truck distances for platoons).

The laser system is composed of two sensors to measure the speed of each truck while passing over the test section, one sensor to measure the inter-truck distances and a last sensor to measure the lateral deviation of each truck in reference to the distance between the right tire of the steer axle and the position of each one of the strain gauges.

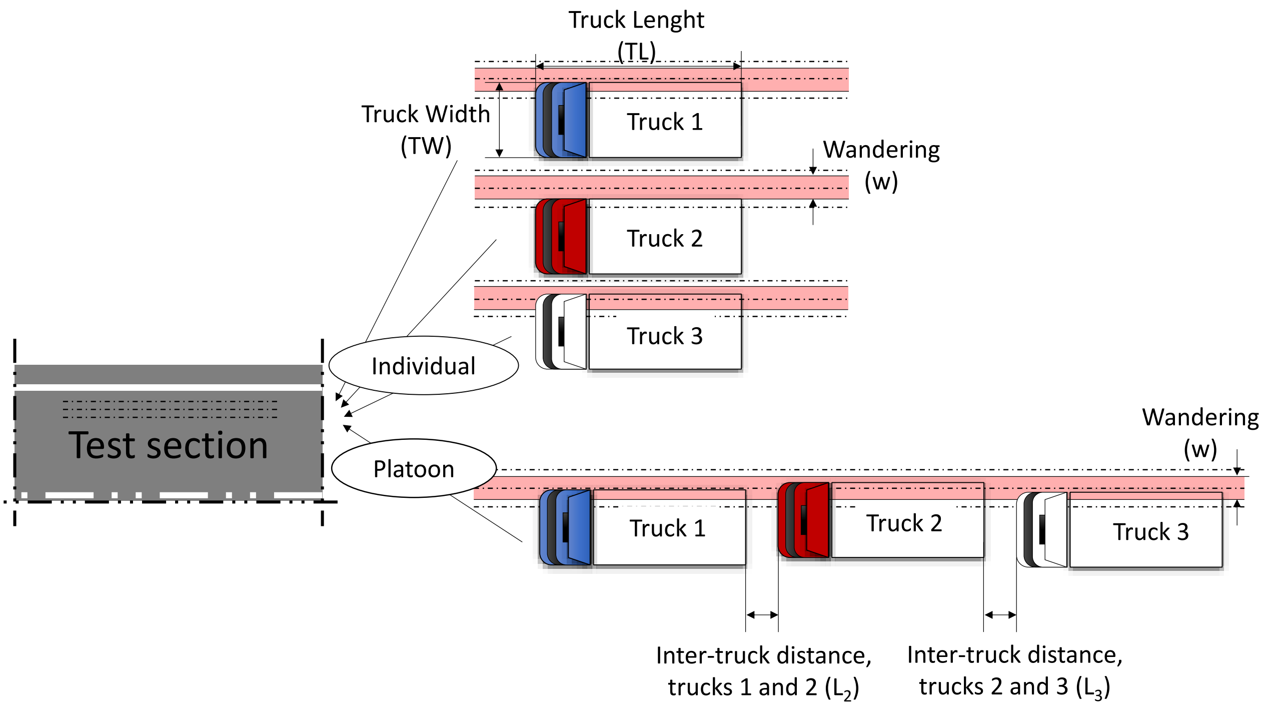


Figure 9: Test scenarios: Individual and Platoon.
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

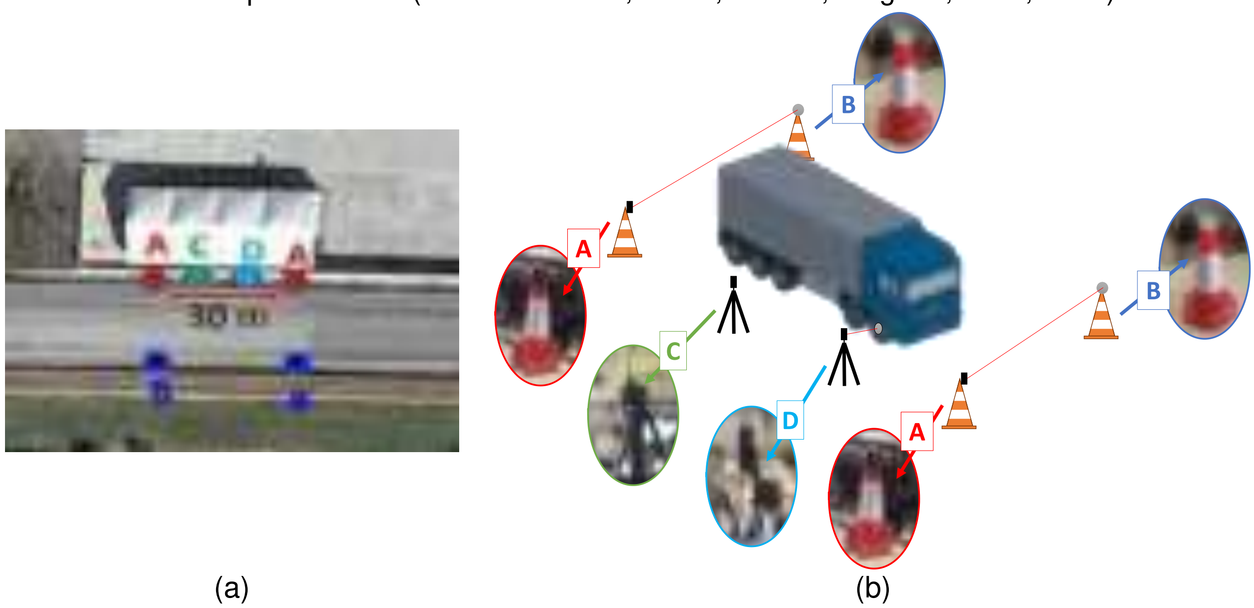


Figure 10: Laser system with the details about the (a) placement of the elements used and (b) the type of elements, where: A and B are cones with lasers and reflective discs used to verify truck

speed, C is the laser to measure inter-truck distances and D is the laser and the disc glued to each truck and used to measure the transversal position and inter-truck distances.
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

The experimental plan was composed of two test campaigns (Figure 11):

1. Winter: from 11 to 12 January 2020, with asphalt temperatures between 4.5 °C and 12.8 °C.
2. Summer: from 29 to 30 August 2020, with asphalt temperatures between 24,9 °C and 32,1 °C.

In both cases, the temperatures of European pavements in service can be even more extreme. However, the values obtained can be considered valid to characterise the effect produced in pavement structures by platooning trucks.

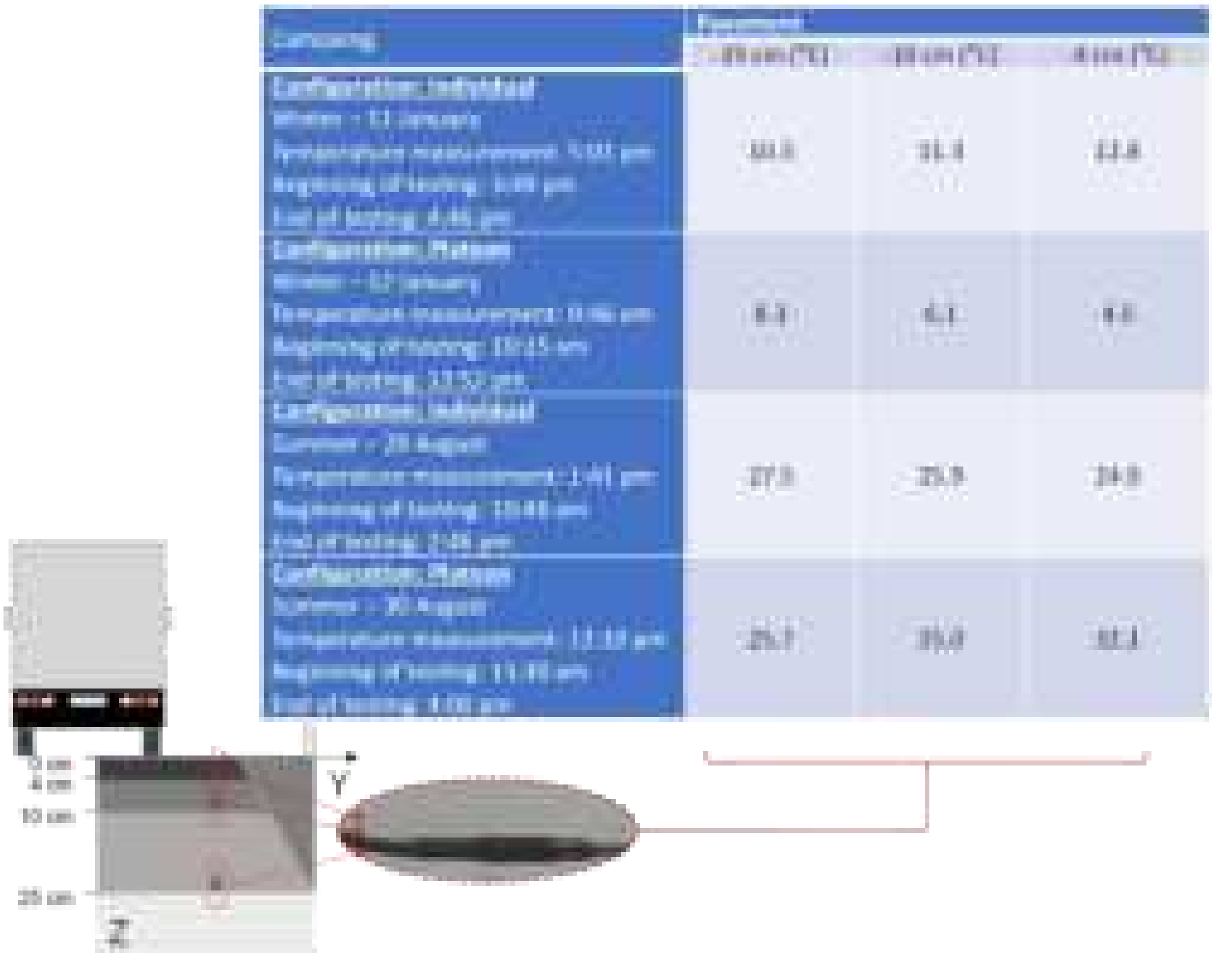


Figure 11: Test campaigns.

3.1.6. Results

These results presented in this section are already published in the following research papers:

- Fatigue life predictions for a European pavement test section subjected to individual and platoon truck configurations (Paulina Leiva-Padilla et al., 2022), published on 6 January 2022 in the Transportation Research Record: Journal of the Transportation Research Board.

- Comparison of the response of an instrumented pavement section under individual and platoon truck loading (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022), published on 22 January 2022 in the International Journal of Pavement Engineering.

3.1.6.1. Descriptions of the signals obtained from instrumentation

Before analysing the data, it is important to describe the signals obtained using the instrumentation placed on site. Figure 12 and Figure 13 show signals obtained for the strain gauges located at 25 cm depth from the surface and a distance of -0.13 m from the strain gauges located 1.05 m from the border of the safety lane, during the passage of truck 1 in the individual configuration and at a speed of 60 km/h.

As can be seen from the shape of the signals, all the strain gauges were working correctly and their location can easily be identified by the time interval and the maximum values obtained after the passage of each axle of the vehicle.

The two figures clearly show that the horizontal strain values measured in summer are higher than the ones obtained in winter, with higher values for the central strain gauges (the grey coloured ones) in the transversal direction, when the right axle tires are passing over them.

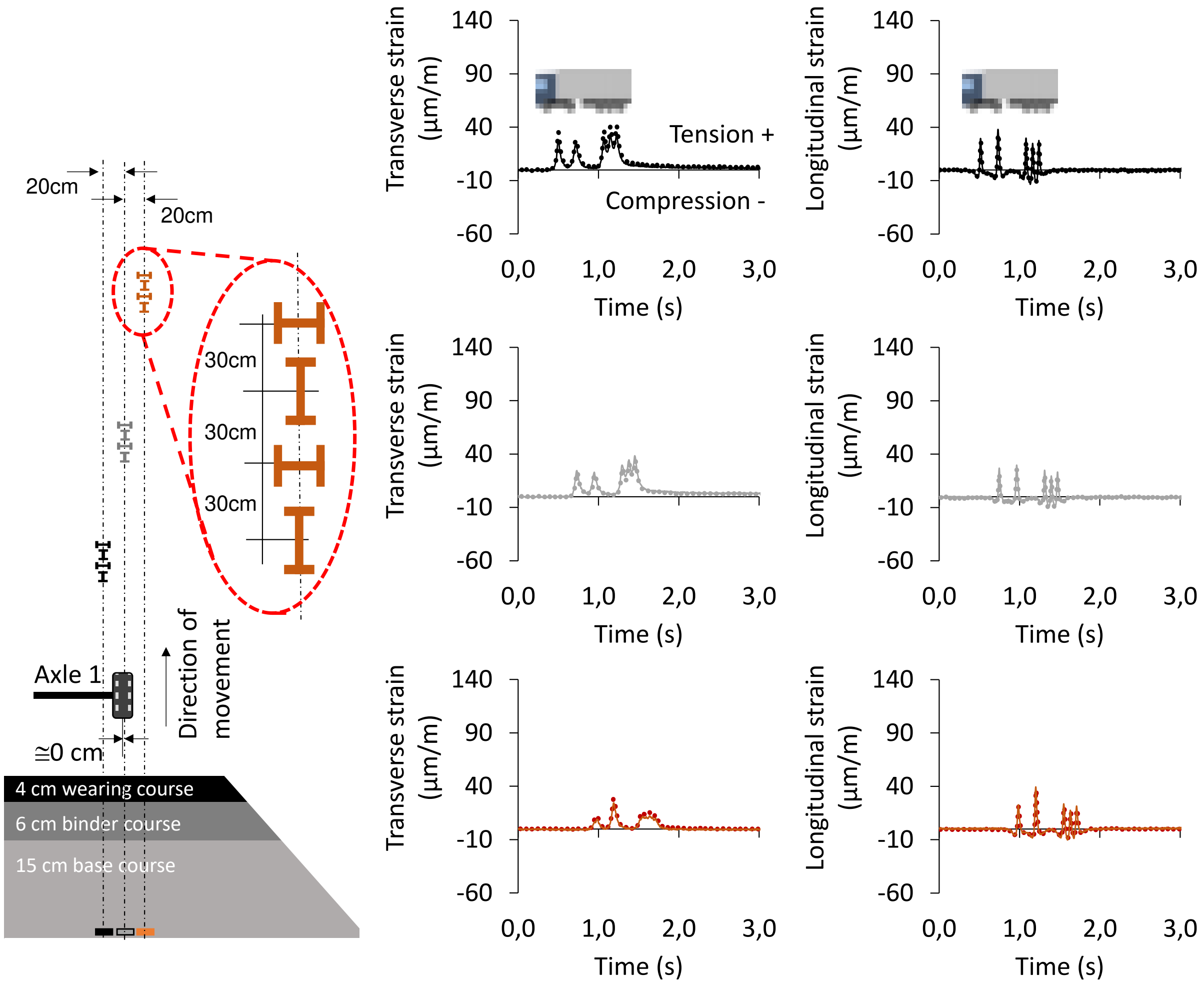


Figure 12: Horizontal strains obtained from run 8 for Truck 1 under individual configuration (Winter campaign, Truck speed = 60km/h, Strain Gauges Depth = 25 cm, Y1 = 0.73m, truck distance from the central strain gauges set = -0,13 m).

Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

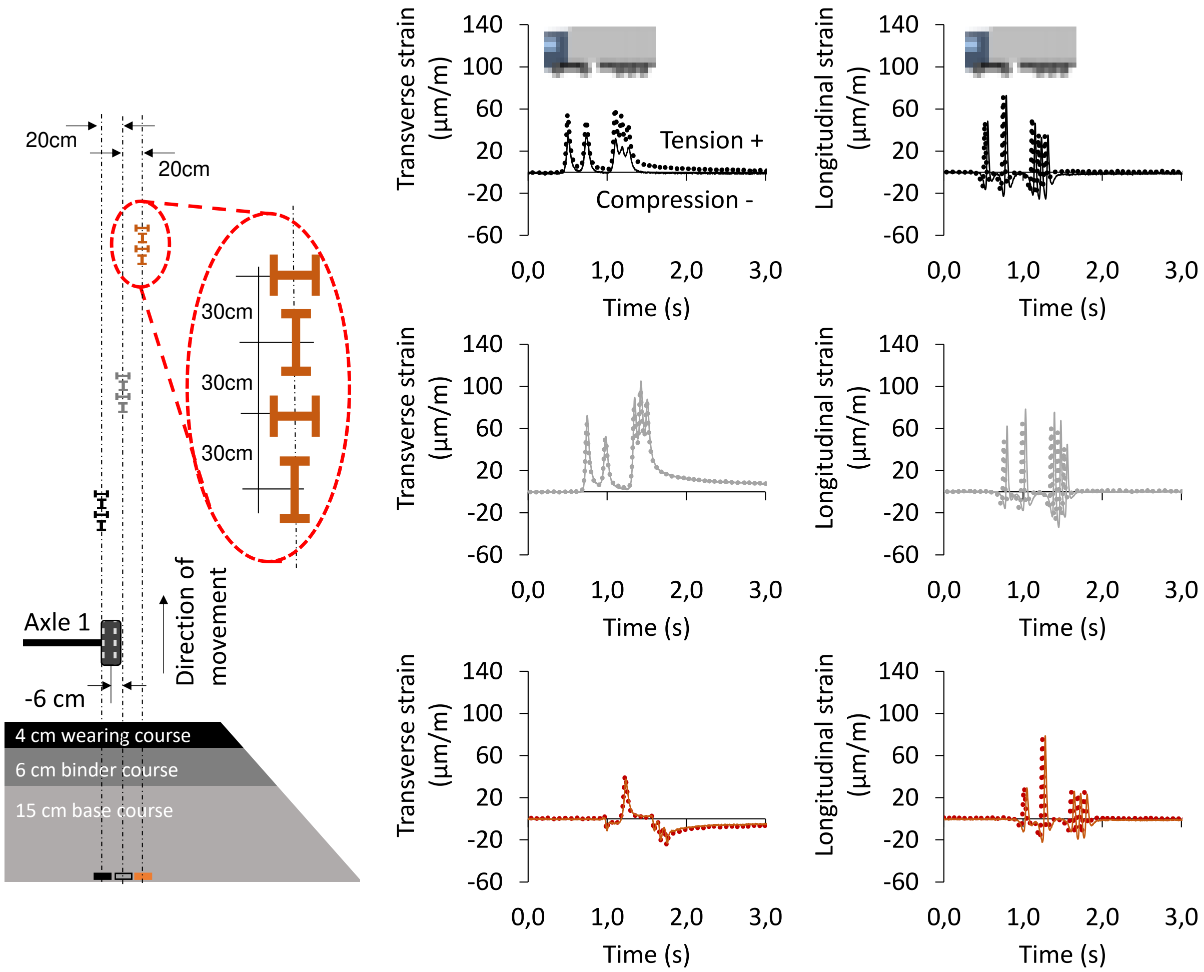


Figure 13: Horizontal strains obtained from run 8 for Truck 1 under individual configuration (Summer campaign, Truck speed = 60km/h, Strain Gauges Depth = 25 cm, Y1 = 0.65m, truck distance from the central strain gauges set = -20cm).
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

Figure 14 shows a comparison of the strain signals obtained under the passage of the trucks in individual and platoon configuration when the truck speed was 40 km/h and the distance from the strain gauges located 1.05 m from the border of the safety lane was approximately zero for all trucks (wandering = 0.04 m, close to zero). This figure shows that:

- As expected, the strain values are higher for summer (the higher temperatures).

- The transverse strain values are higher than the longitudinal ones.

- There is a slow strain recovery after the passage of each truck, this produces a strain accumulation for the transversal strain values, which seems to be slightly higher in the platoon configuration and therefore is analysed in next sections in this report.

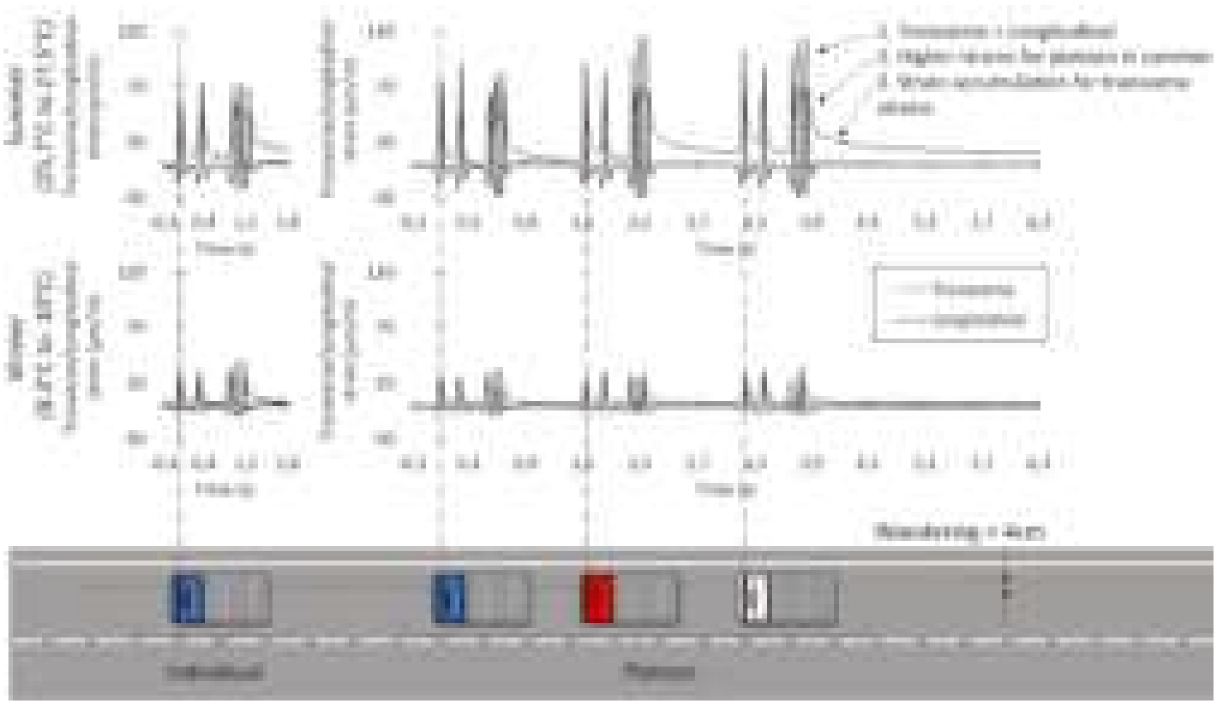


Figure 14: Example of signals obtained for individual trucks and platoons (truck speed = 40 km/h, strain gauges at 25 cm depth from the surface).
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

3.1.6.2. Data repeatability and reproducibility

Considering that there was no loss of any strain gauge during construction, the repeatability and reproducibility of the data obtained were evaluated by comparing the maximum strain values obtained during the passage of each axle of the truck.

In the case of repeatability, the data was analysed according to the following conditions (Figure 15):

- Same operator (Truck 1).
- Same load configuration: individual truck.
- Same lateral distance from the strain gauge.
- Same test truck.
- Similar strain gauges (T1, T2, L1 and L2).
- Short intervals of time between passages (run 5: 11/01/2020, 16:02; run 26: 12/01/2020, 10:11).

The conclusions obtained from the analysis of variance (ANOVA) indicated 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 that the data obtained during testing has good repeatability.

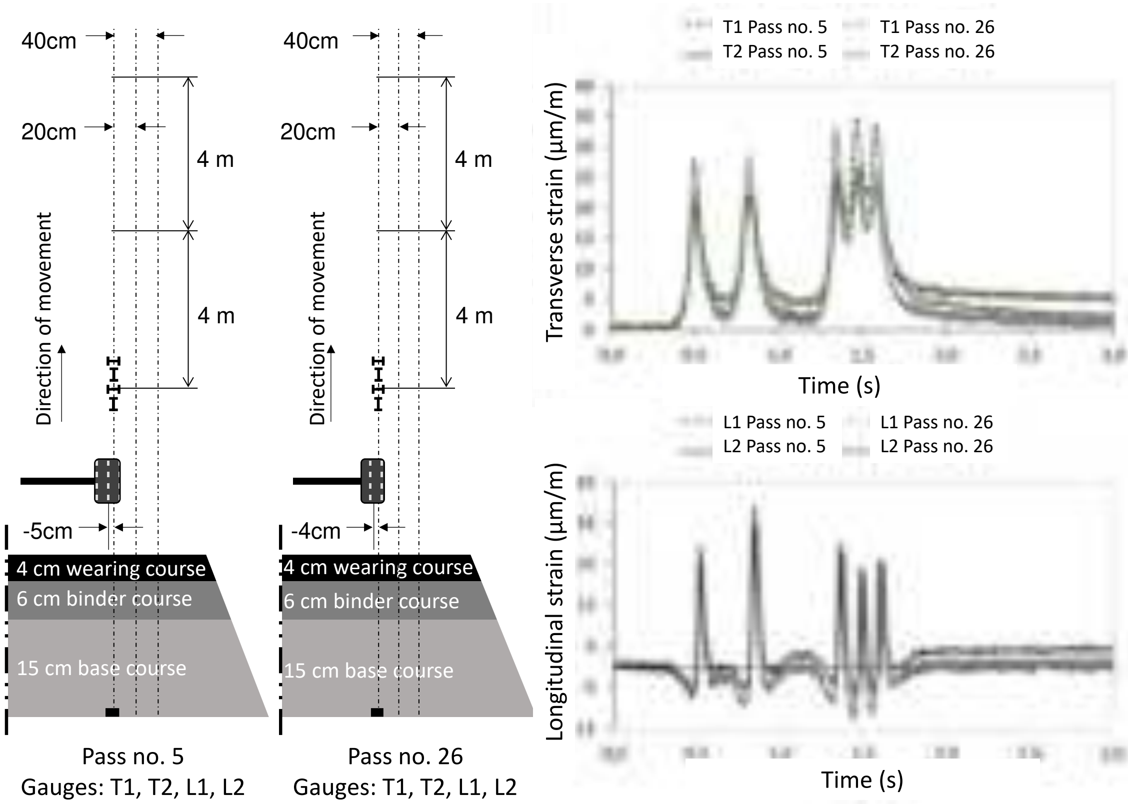


Figure 15: Analysis 1: Repeatability, Truck 1, Truck speed = 60 km/h, Individual Configuration, Transversal (T) and Longitudinal (L) strain gauges, winter campaign.
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

In the case of reproducibility, the data was analysed according to the following conditions (Figure 16):

- Same load configuration: individual truck.
- Same test section.
- Same wandering.
- Different operators (truck 1, truck 2, and truck 3).
- Different strain gauges.

The ANOVA of the data indicated 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 collected data.

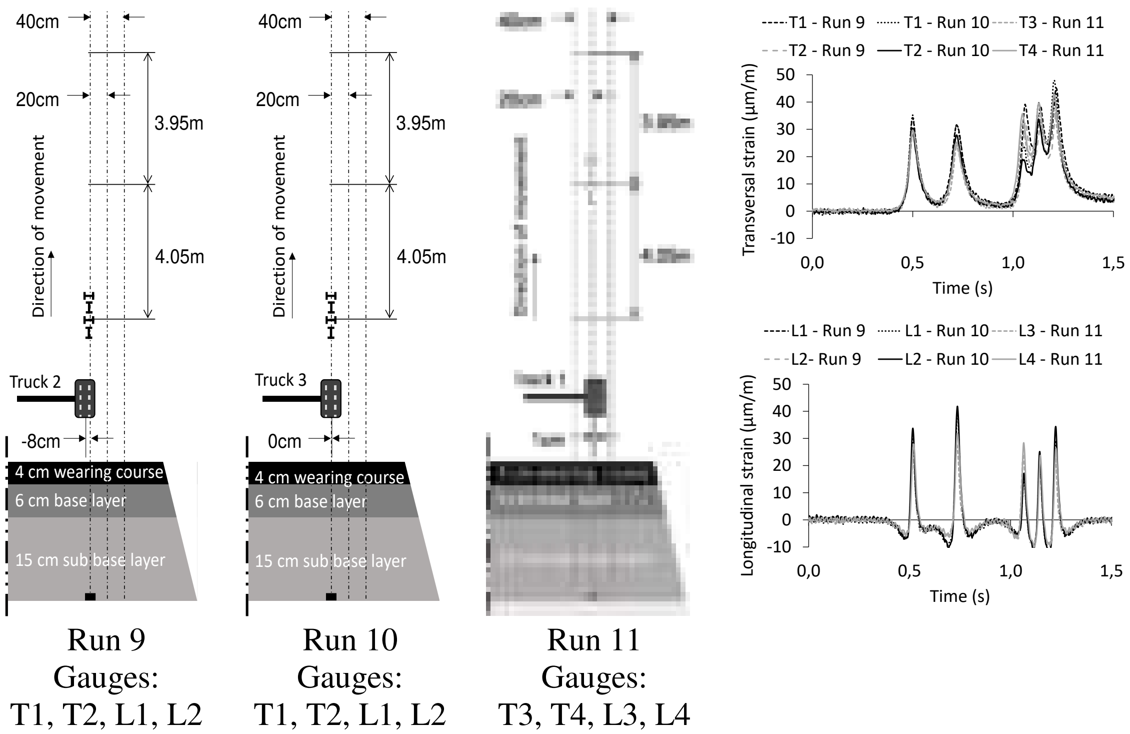


Figure 16: Analysis 2: Reproducibility, considered truck speed = 60 km/h, Individual Configuration, Transversal (T) and Longitudinal (L) strain gauges.

Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

3.1.6.3. Lateral deviation (wandering)

Since the truck platooning configuration was simulated by human-driven 5-axle semitrailer trucks, as shown in Figure 17, the lateral deviation measured from the right tire of the steer axle to each strain gauge ranged from -0,66 m to 0,36 m, with an average value of -0,17 m and a standard deviation of 0,20 m. According to Zhou et al. (2019) studies, human driven and autonomous trucks could be characterised by a normally distributed lateral positioning with standard deviations of 0,25 m and 0,07 m, respectively. Therefore, the results obtained seem to be appropriate to represent both (1) a lateral deviation close to zero, and (2) higher variances in the lateral deviations (wandering patterns) of truck platoons.

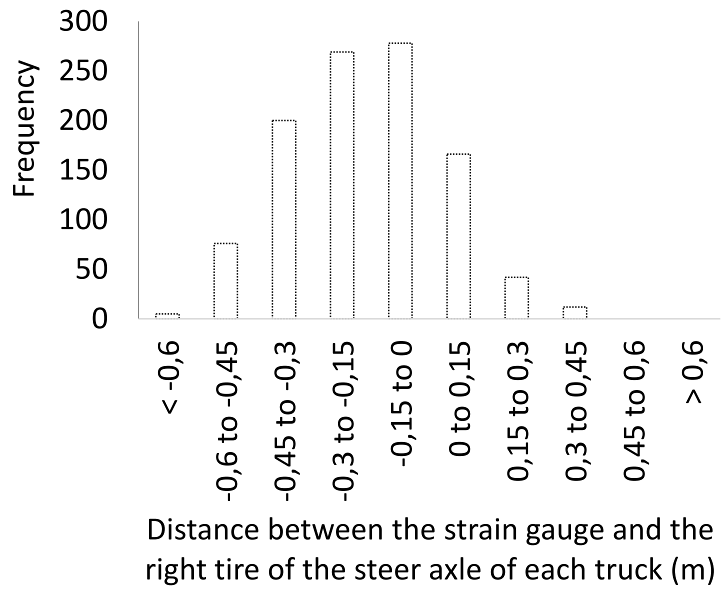


Figure 17: Distribution of lateral distances between the strain gauges and the right front tire for the whole test

Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

3.1.6.4. Instrumentation versus laser measurements

As shown in Figure 18, Figure 19, Figure 20 and Figure 21, the information obtained from the laser measurements and the recorded strain signals, concerning truck speeds and positions were compared, and the following results were obtained:

- For truck speeds (Figure 18 and Figure 19): for both winter and summer, the results indicate a small variation and similar values for both methods.
- For inter-truck distances (Figure 20 and Figure 21): the value of 0,8 s was successfully achieved with higher variations at the highest truck speed (80 km/h), due to truck driver's increased difficulty to maintain constant time-distances between trucks at higher speeds.

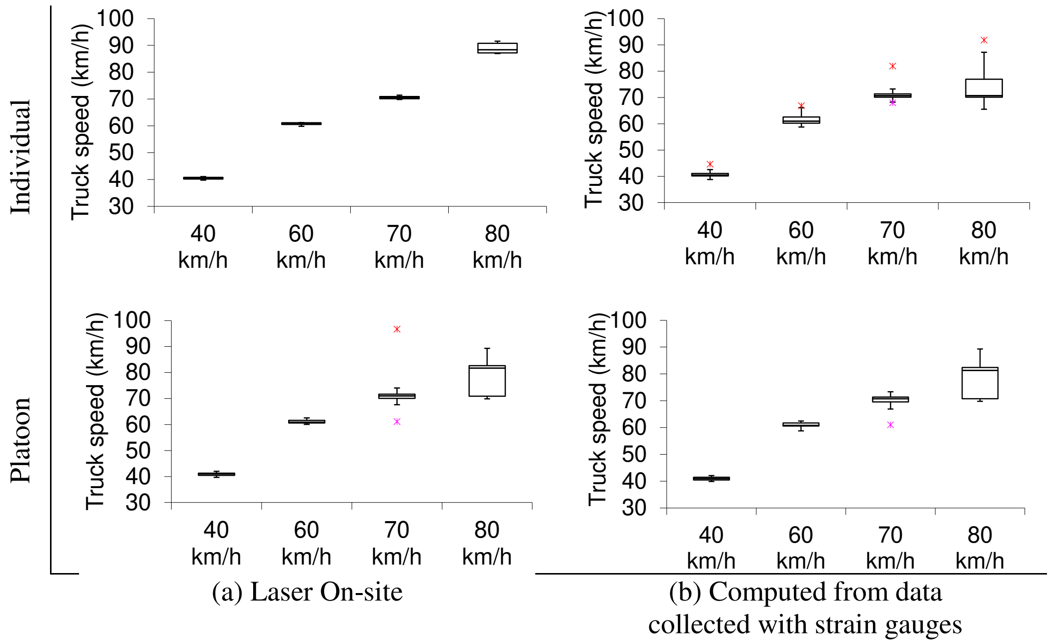


Figure 18: Truck speeds for both individual and platoon configuration (winter campaign).
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

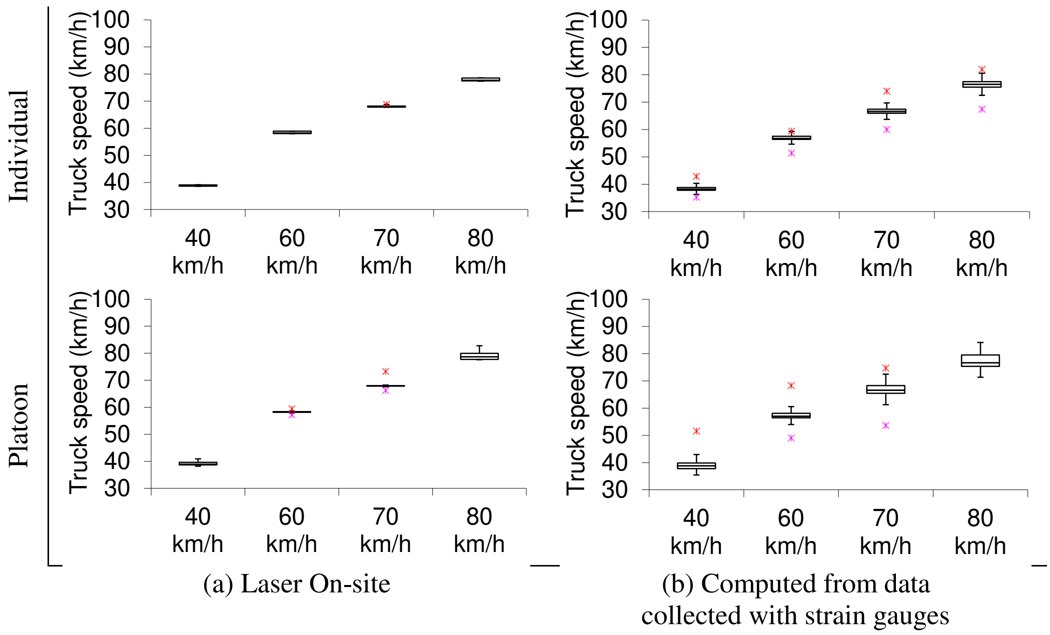


Figure 19: Truck speeds for both individual and platoon configuration (summer campaign).
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

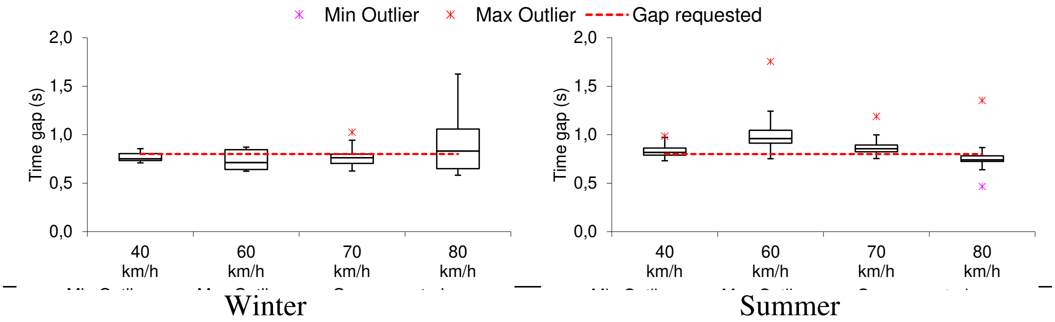


Figure 20: Inter-truck time gaps in the platoon configuration.
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

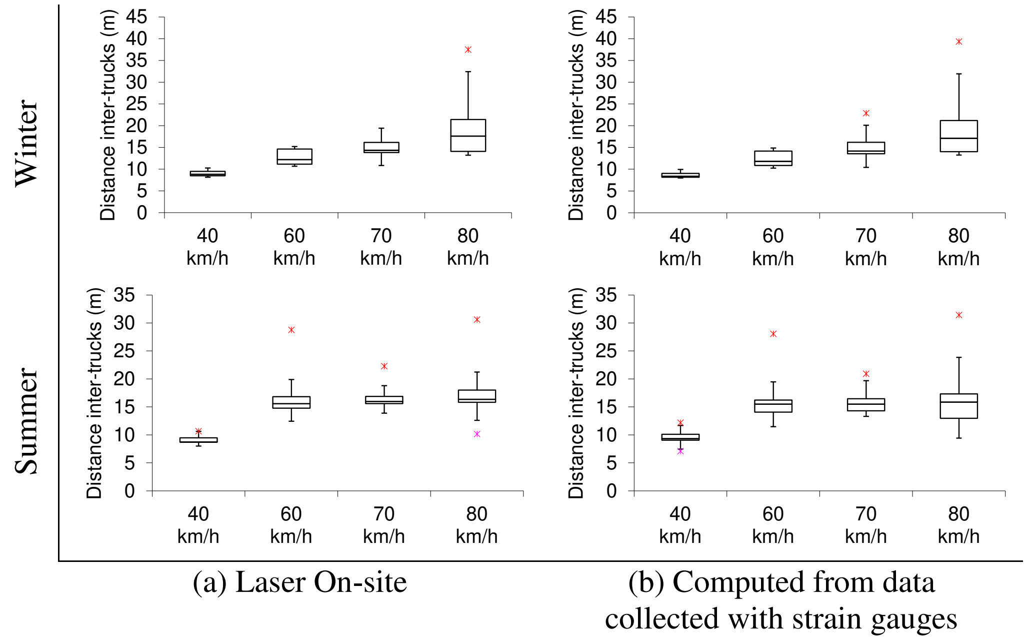


Figure 21: Inter-truck distances for a time gap of 0.8 s in the platoon configuration.
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

3.1.6.5. Individual versus platoon configurations

Once the correct simulation of the truck platoon configurations was verified, the transversal strain signals were analysed, considering the four critical strain levels shown in Figure 22. These four strain levels correspond to the maximum strain values obtained under the passage of the steer, driven, and trailer tridem axles, and the accumulated strain 0,7 s after the passage of the vehicle. The selection of an interval of 0,7 s to determine the accumulated strain level was based on getting a comparable point between individual and platoon configurations, due to the fact that the time gap between trucks in the platoon configuration presented some testing variability.

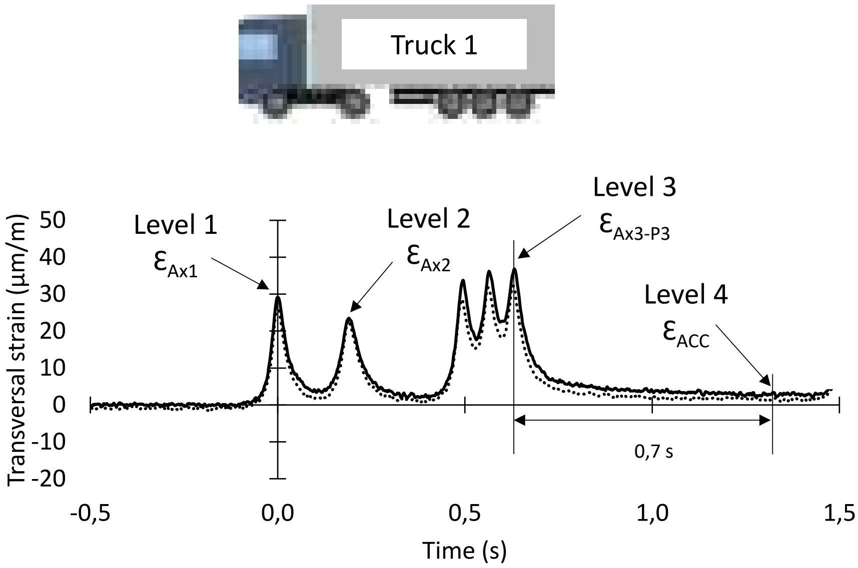


Figure 22: Critical strain levels used in this study.
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

The strain values obtained for all the truck passages, and for each critical strain considered are shown in Figure 23, Figure 24, Figure 25 and Figure 26, for the individual and platoon configurations and for the winter and summer campaigns. As explained before, each dot corresponds to the maximum strain value obtained for the passage of each axle of each truck (blue for truck 1, red for truck 2, and white for truck 3) or the accumulated strain value obtained 0.7 s after the passage of each truck. Figure 26 and Figure 28 shows the values obtained for each truck passing individually and Figure 27 and Figure 29 shows the values for each truck while they are in platoon configuration (truck 1 in front, followed by truck 2 and truck 3). Even if the dots correspond to measurements with different laterally positioned strain gauges, the lateral position has been correspondingly corrected and referenced to the black dashed line in the figures. The dashed line corresponds to the position of the central set of strain gauges, which are positioned at 1.05 m from the save guard line (see Figure 4). As seen in the figures and as expected, the strain values decrease when the lateral distance of each axle from the strain gauges increases, with higher values obtained for the summer campaign. It can be noticed that the dual tires of the drive axle lead to a wider distribution of the maximum values, on the corresponding graphs.

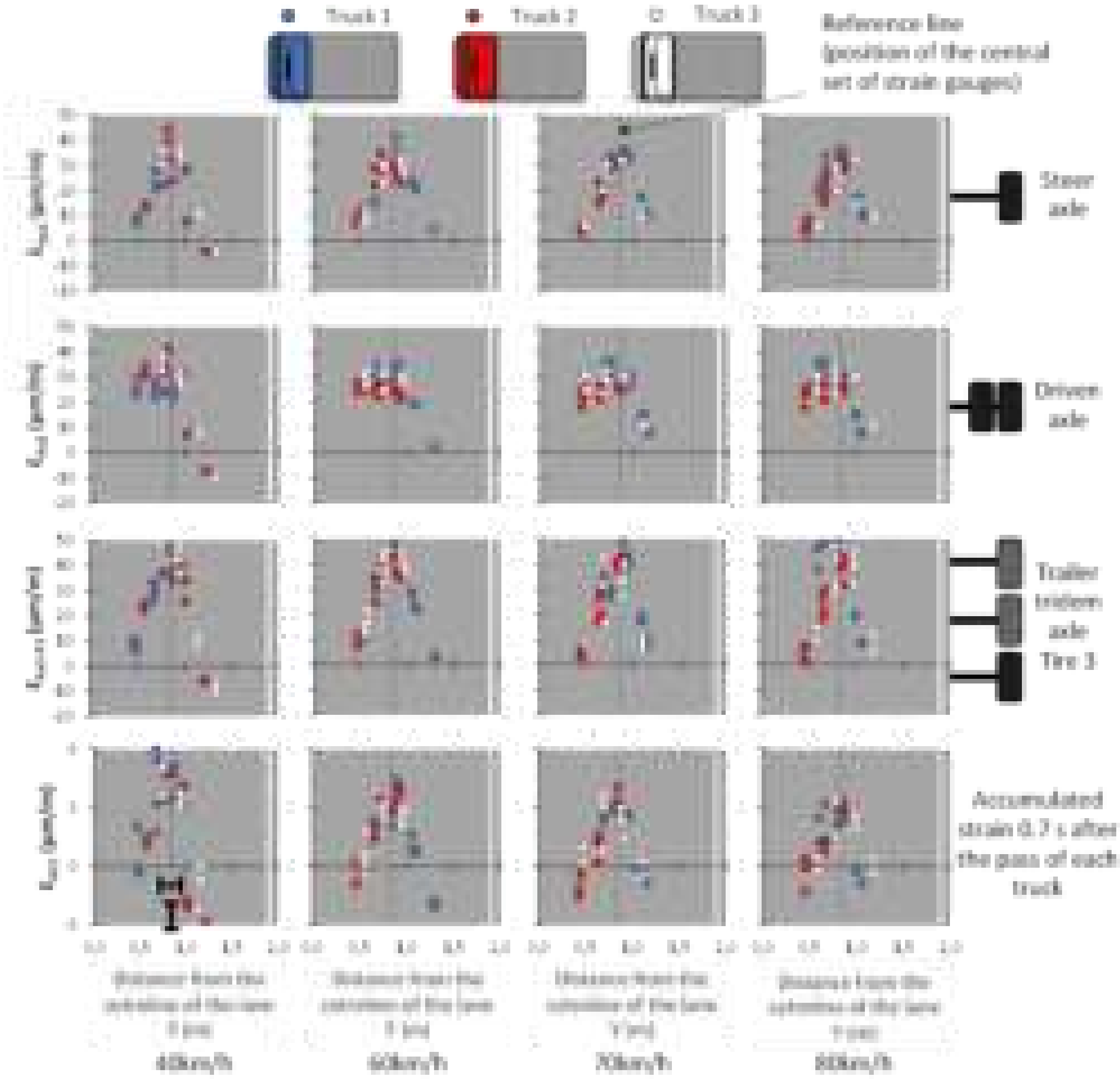


Figure 23: Transversal strains at each point of analysis for the individual truck scenario (winter campaign, reference line at 0.85 m from the centre of the lane).
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

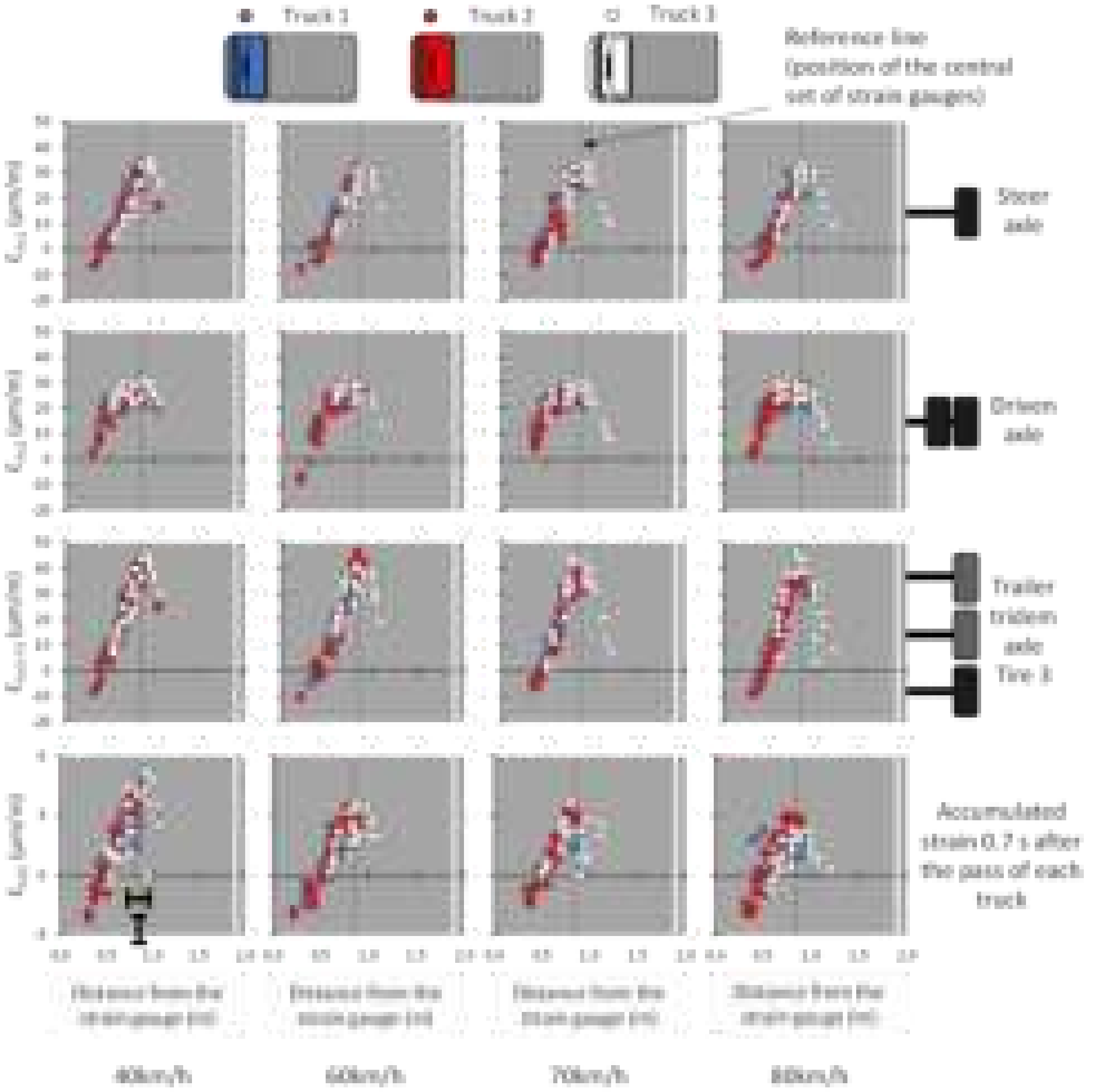


Figure 24: Transverse strains at the points of analysis for the platoon configuration (winter campaign, reference line at 0.85 m from the centre of the lane).
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

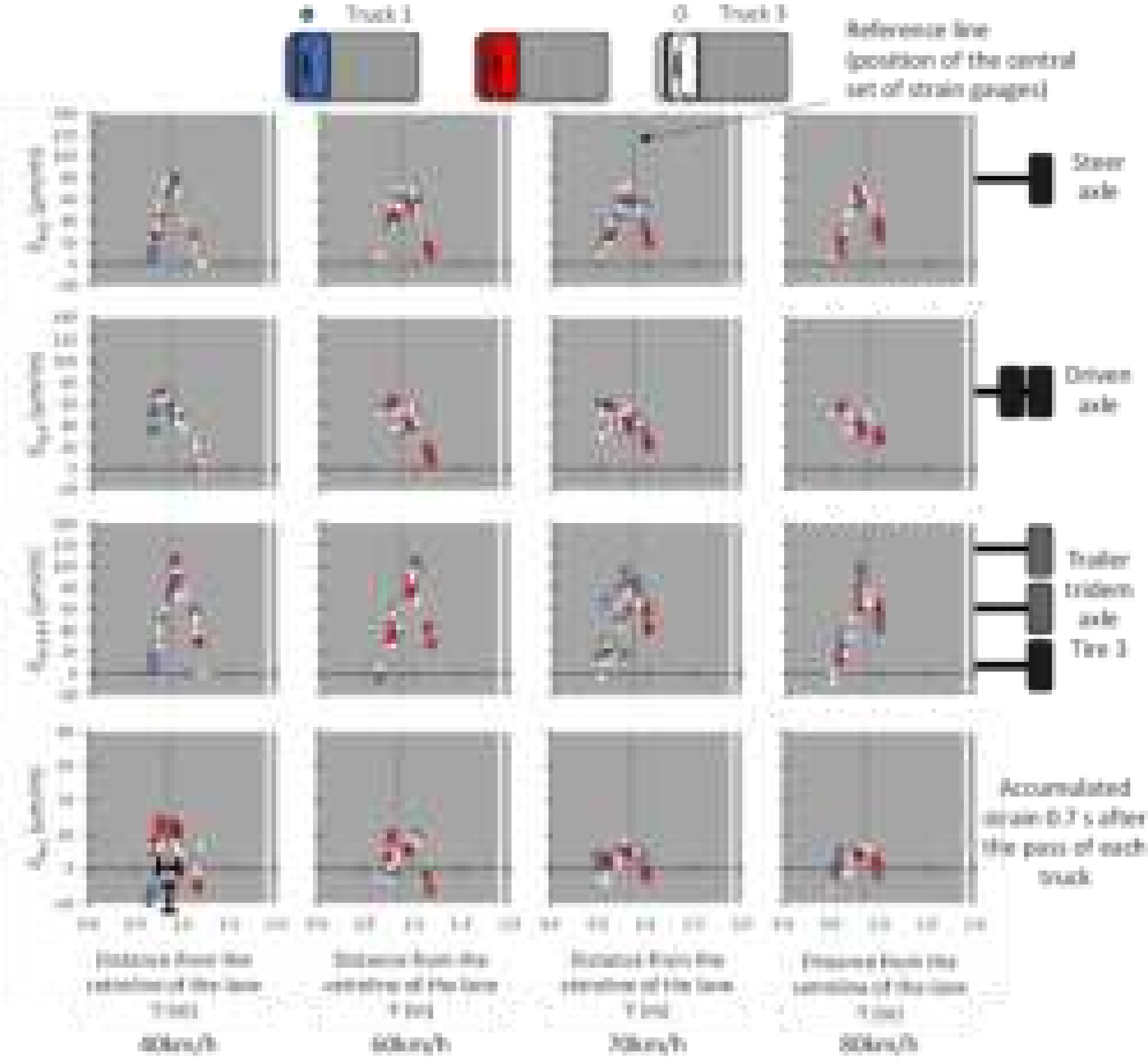


Figure 25. Transversal strains at the points of analysis for individual configuration (summer campaign, reference line at 0.85 m from the centre of the lane).
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

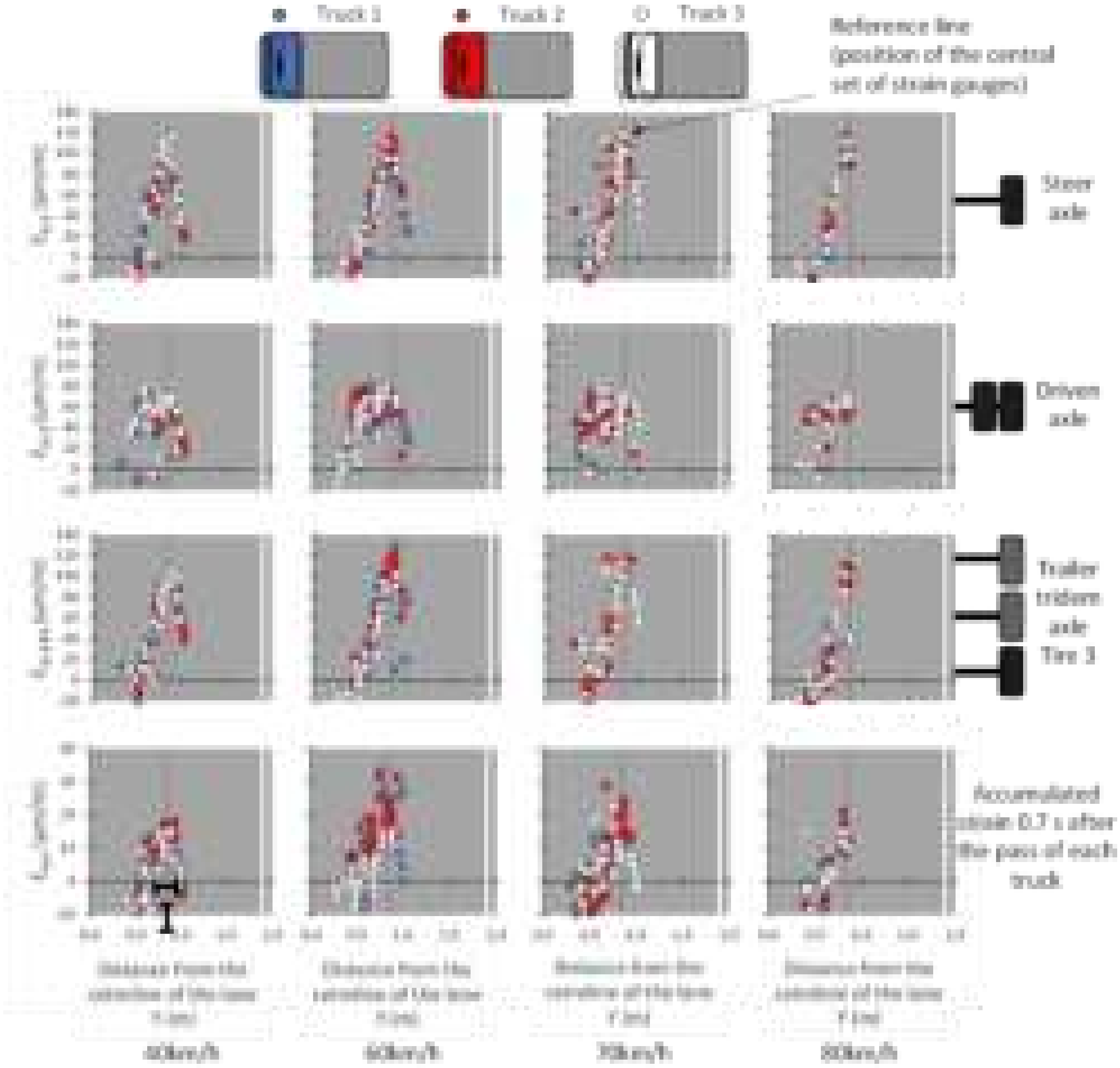


Figure 26. Transversal strains at the points of analysis for the platoon configuration (summer campaign, reference line at 0.85 m from the centre of the lane).
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

To analyse the effect of including a lateral deviation for each truck in the platoon (wandering), the data was grouped according to each truck's lateral distance relative to each corresponding strain gauge (interval of wandering, Figure 27). The following sections describe the values obtained for an interval of wandering of 30 cm and compares them with values obtained with an extended interval of wandering of 50 cm, for the summer campaign. In each case, the data was selected by considering all the truck passes which were inside each respective interval.

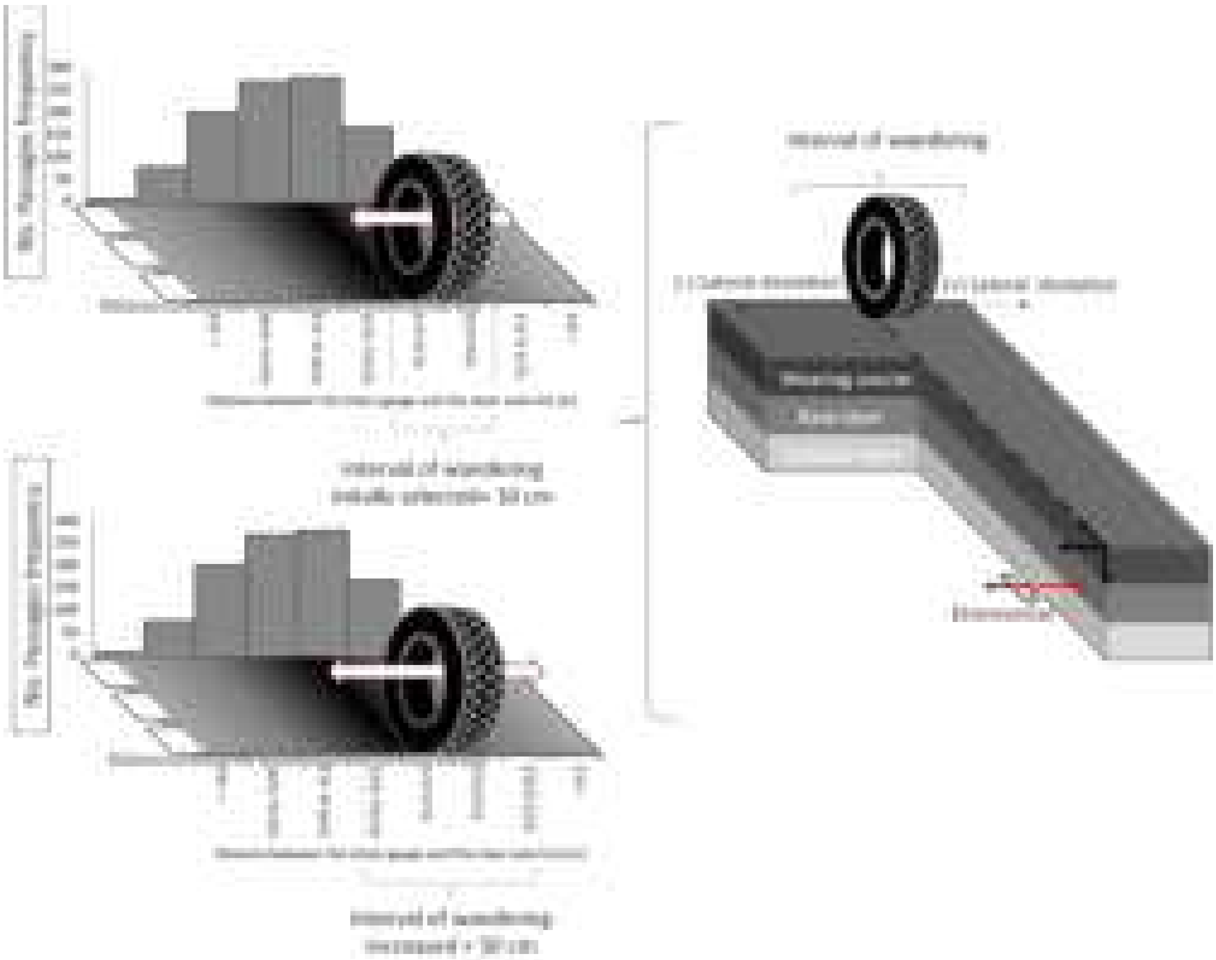


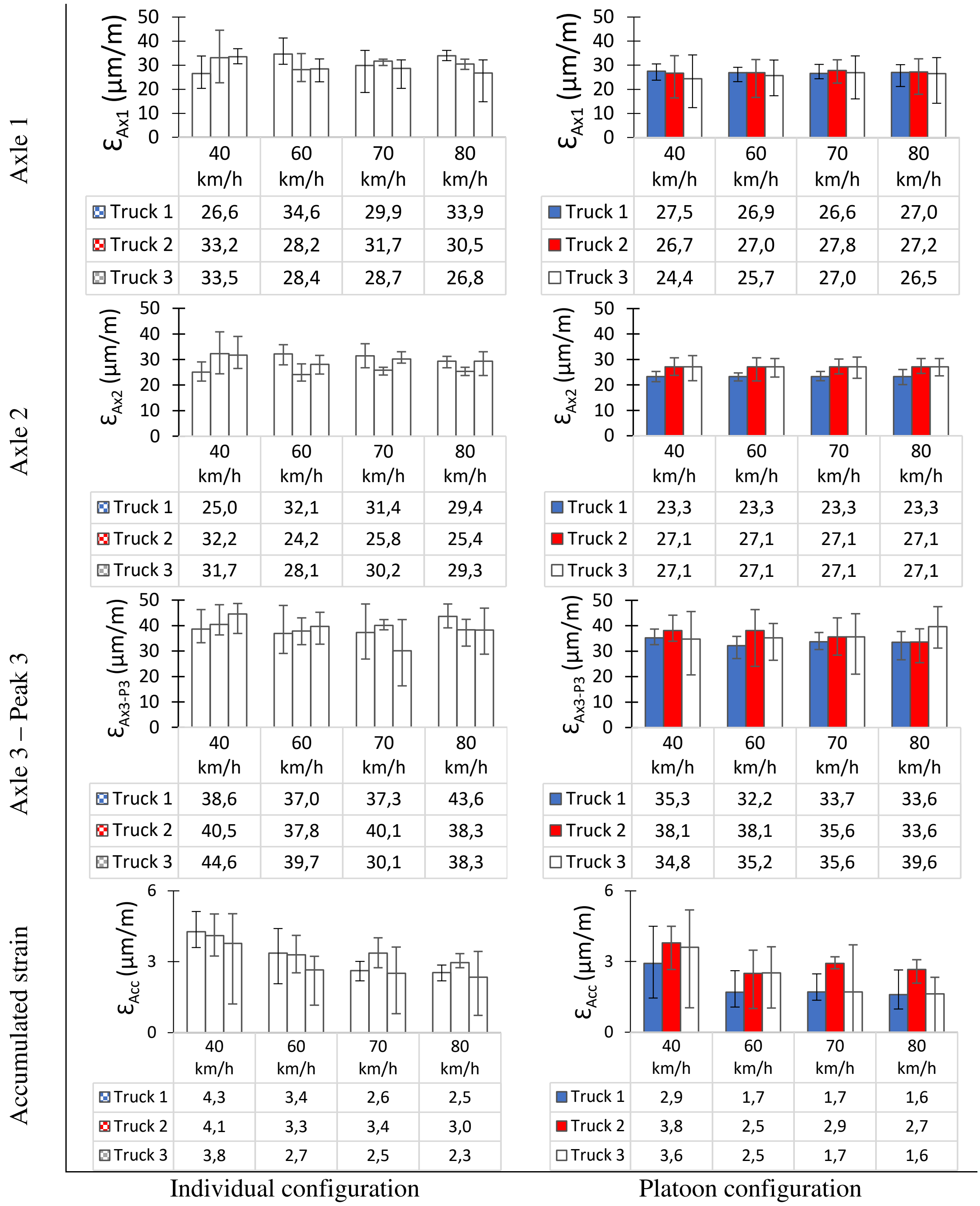
Figure 27. Intervals of wandering selected during the analysis.
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

Interval of wandering = 30 cm

Figure 28 and Figure 29 show the values obtained for each of the selected critical strains, for a wandering of 30 cm. Figure 30 shows a comparison in percentage between the strains obtained during the winter campaign and the summer campaign. The results show that:

- For the winter campaign, the values do not show any clear difference between the individual and the platoon configuration. Additionally, the values seem to be very similar for axle 1 and axle 2, and higher for axle 3. In the case of the accumulated strains, they tend to decrease with increasing test speed.

- For the summer campaign, the values are significantly higher for the platoon configuration than for individual trucks. The values obtained also differ for each axle. It is important to mention here that asphalt materials by nature have a viscoelastic behaviour that depends on temperature and speed/frequency of loading. Such materials, at certain temperatures, as is the case of the example under study in this report, have a delayed recovery response. In this sense, this delayed response under repeated loads generated by the vehicle traffic, lead to accumulated strains. A higher accumulation of strains can reduce the mechanical capacity of the material and therefore the life of the pavement structure. This could be therefore reflected in terms of cracks for the structural response monitored in this case study (strains in the asphalt layers). This effect will be illustrated in the next section related to numerical modelling. The statistical comparison between both campaigns shows that for a level of confidence of 95%, there is no difference between individual trucks and platoons for winter, while in summer there is a significant difference between individual trucks and platoons. The highest differences are observed for the accumulated strain values. However, it is important to consider that this effect could be reduced by increasing the lateral deviation of the trucks in the platoon, reducing the loads or increasing the inter-truck time gaps. The variation of these parameters is evaluated later in this report.



Axle 1 – Individual configuration

	40 km/h	60 km/h	70 km/h	80 km/h
Truck 1	26,6	34,6	29,9	33,9
Truck 2	33,2	28,2	31,7	30,5
Truck 3	33,5	28,4	28,7	26,8

Axle 1 – Platoon configuration

	40 km/h	60 km/h	70 km/h	80 km/h
Truck 1	27,5	26,9	26,6	27,0
Truck 2	26,7	27,0	27,8	27,2
Truck 3	24,4	25,7	27,0	26,5

Axle 2 – Individual configuration

	40 km/h	60 km/h	70 km/h	80 km/h
Truck 1	25,0	32,1	31,4	29,4
Truck 2	32,2	24,2	25,8	25,4
Truck 3	31,7	28,1	30,2	29,3

Axle 2 – Platoon configuration

	40 km/h	60 km/h	70 km/h	80 km/h
Truck 1	23,3	23,3	23,3	23,3
Truck 2	27,1	27,1	27,1	27,1
Truck 3	27,1	27,1	27,1	27,1

Axle 3 – Peak 3 – Individual configuration

	40 km/h	60 km/h	70 km/h	80 km/h
Truck 1	38,6	37,0	37,3	43,6
Truck 2	40,5	37,8	40,1	38,3
Truck 3	44,6	39,7	30,1	38,3

Axle 3 – Peak 3 – Platoon configuration

	40 km/h	60 km/h	70 km/h	80 km/h
Truck 1	35,3	32,2	33,7	33,6
Truck 2	38,1	38,1	35,6	33,6
Truck 3	34,8	35,2	35,6	39,6

Accumulated strain – Individual configuration

	40 km/h	60 km/h	70 km/h	80 km/h
Truck 1	4,3	3,4	2,6	2,5
Truck 2	4,1	3,3	3,4	3,0
Truck 3	3,8	2,7	2,5	2,3

Accumulated strain – Platoon configuration

	40 km/h	60 km/h	70 km/h	80 km/h
Truck 1	2,9	1,7	1,7	1,6
Truck 2	3,8	2,5	2,9	2,7
Truck 3	3,6	2,5	1,7	1,6

Figure 28: Comparison of the strains at the different points of analysis for the individual and platoon configuration when wandering = 30 cm in the winter campaign.
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

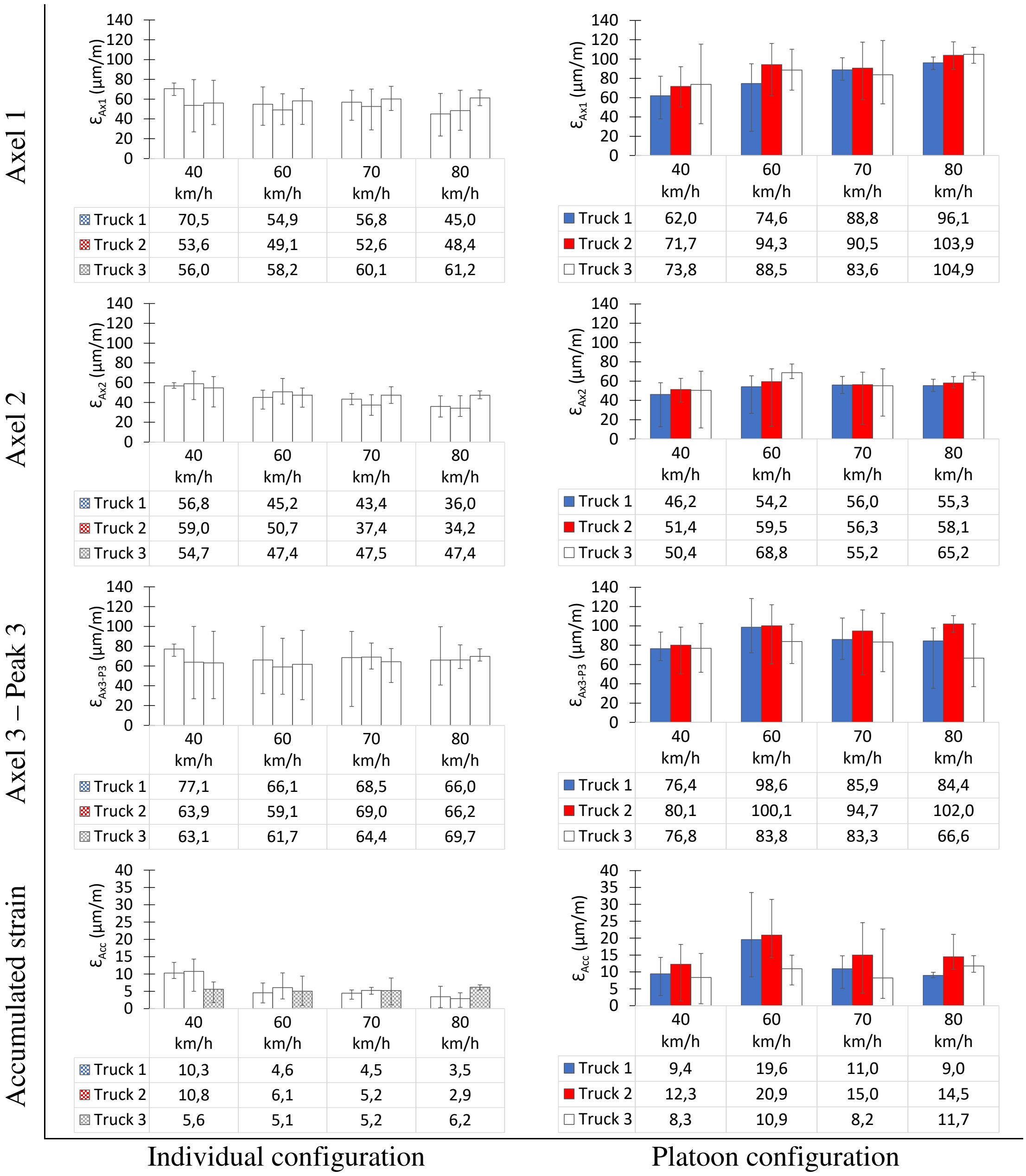


Figure 29: Comparison of the strains at the different points of analysis for the individual and platoon configuration when wandering = 30 cm in the summer campaign.

Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

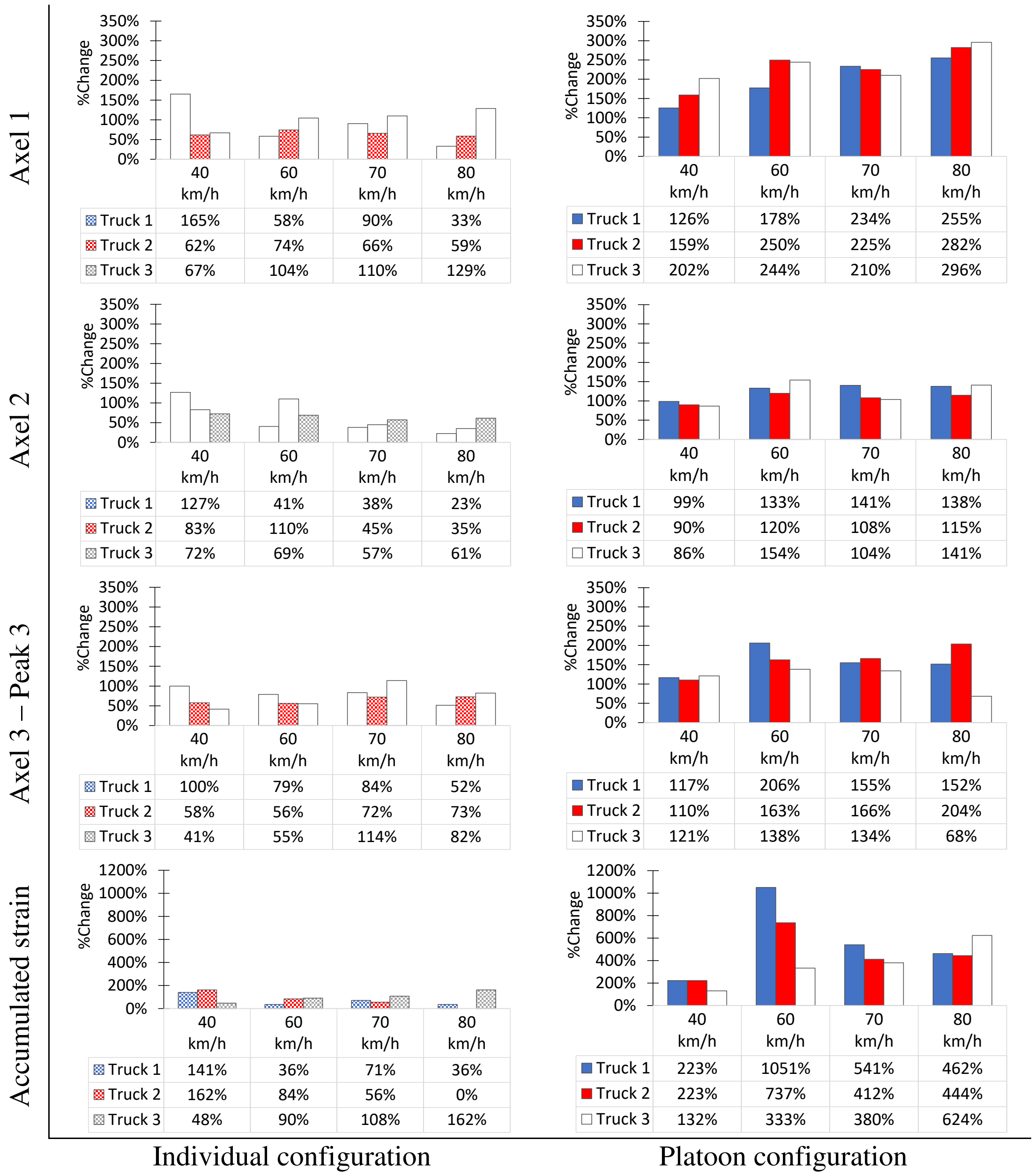


Figure 30: Strain increase (in percentage) for each point of analysis comparing winter and summer campaigns.

Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022)

Interval of Wandering = 30 cm vs Interval of Wandering = 50 cm at high temperatures

Figure 31 shows the comparison between the average values obtained for a wandering equal to 30 cm and when the wandering is increased to 50 cm in the platoon truck configuration. The percentages of change shows that the maximum strain values can be reduced for all the cases, by as much as 29 % for the maximum strains obtained under the axles and 53 % for the accumulated strain values 0,7 s after each truck pass. Considering that the fatigue law for asphalt materials is a power law, with an exponent close to 5, this strain reduction could lead to an important reduction in pavement fatigue damage, as will be described in section 2.6.6.

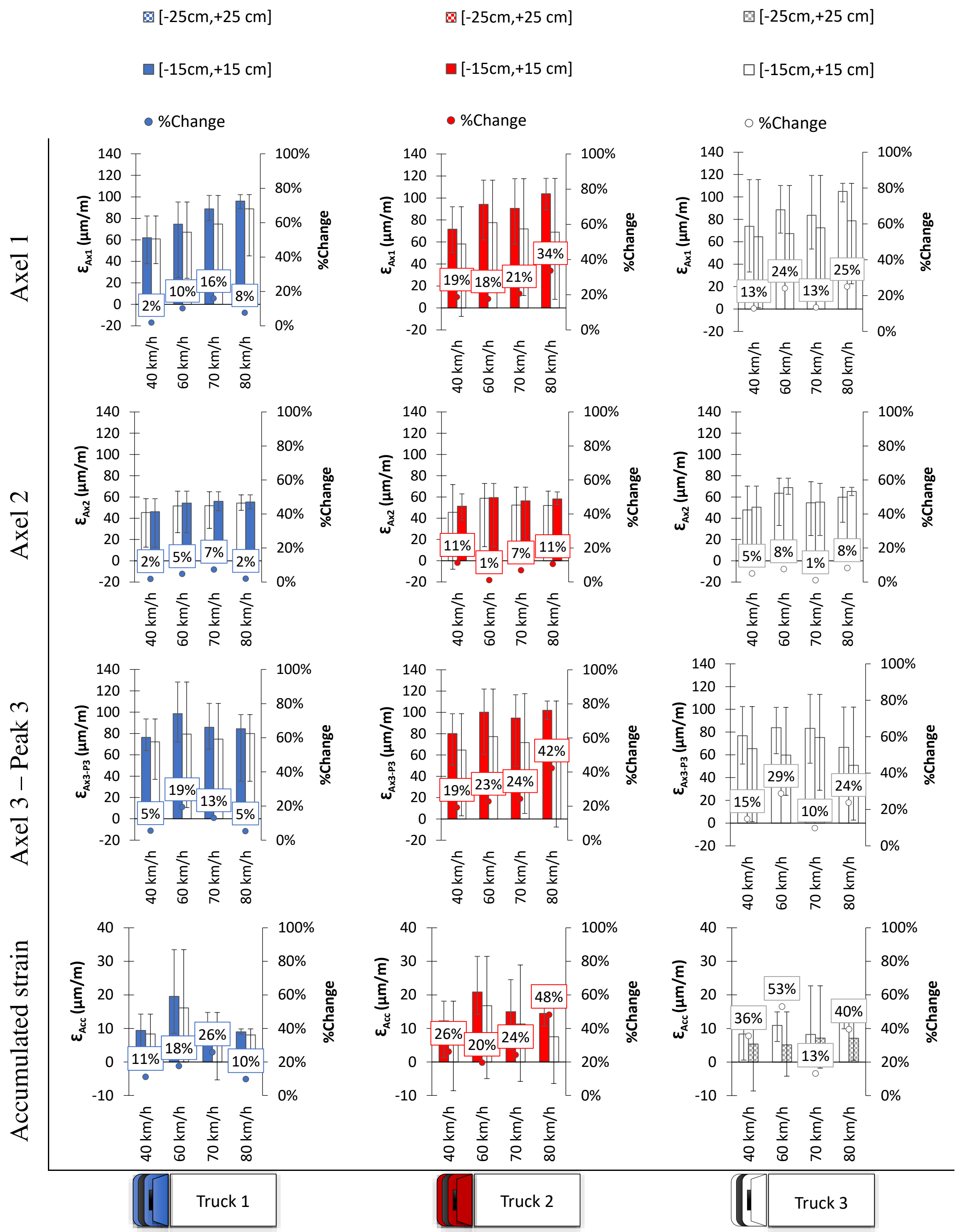


Figure 31: Strain reduction produced by the extension of the wandering for the summer campaign in the platoon configuration.

Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).

Fatigue life predictions

As shown in Figure 32, to evaluate how platooning trucks can change the fatigue performance of the pavement section under study, four scenarios of analysis were defined. These scenarios are based on different assumptions of platoon penetration, with a reduced wandering of 20 cm (which is even lower than the tire widths, equal to 25,5 cm and 28,5 cm). Each scenario is compared to a reference scenario which represents a condition with trucks in individual configurations.

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

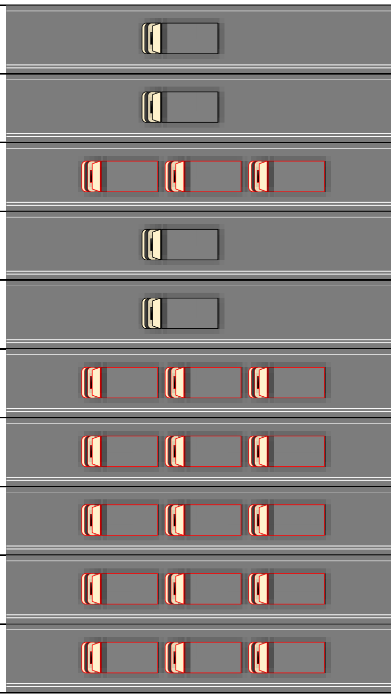


Figure 32: Scenarios of analysis of the impact of platoons (ADT: Average Daily Traffic).
Note: reprinted from (Paulina Leiva-Padilla et al., 2022).

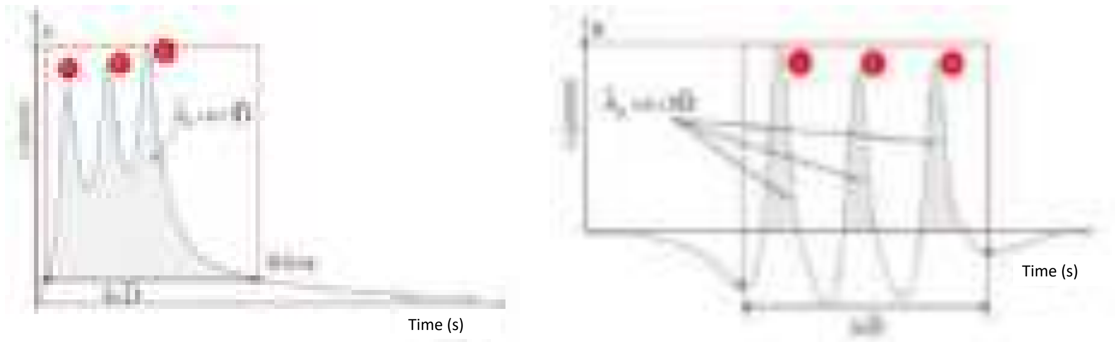
The comparison is based on the use of the multiple-axle fatigue model shown in Equation 1, proposed by Homsi in 2016 (F. Homsi et al., 2012; Farah Homsi et al., 2010, 2012, 2016) to determine the remaining number of cycles to fatigue of the pavement test section, based on the characteristic parameters of the longitudinal or transversal strain signal obtained by the passage of the steer, driven and trailer tridem axle of each truck.

Equation 1

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

(F. Homsi et al., 2012; Farah Homsi et al., 2010, 2012, 2016)

Where (see Figure 1), ε: strain intensity (peak strain level) produced by the passage of the reference axle (tridem axle in the example of Figure 33), Np: number of peaks of the strain signal, $\hat{A}n$: positive area under the loading signal in the transversal/longitudinal direction divided by the peak strain and its duration, $\bar{D}$: Duration of the loading signal divided by the number of peaks (in seconds), regression coefficients and error (for the transverse signal used in this report, $a = -4.58$, $b = -0.84$, , $c = 1.31$, , and $e = 15.22$)



(a) Transversal (b) Longitudinal

Figure 33: Parameters for the characterization of a transversal/longitudinal strain signal
Note: reprinted from (F. Homsi et al., 2012; Farah Homsi et al., 2010, 2012, 2016).

By using the fatigue cycles obtained and the cumulative damage concept, the Coefficient of Aggressiveness (CA) of each vehicle in the individual and platoon configuration was determined. As Equation 2 shows, the CA is used in France to compare the fatigue damage produced by different vehicle configurations. CA is defined as the α-factor (in percentage) of the ratio between the fatigue damage produced by a given truck and the damage produced by the equivalent standard axle (ESAL, single axle with dual wheels, loaded at 130 kN in the French pavement design method).

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

Equation 2 (Paulina Leiva-Padilla et al., 2022)

Where, the factor a corresponds to the accepted level of damage corresponding to the end of service life of the pavement, d_{truck} is the fatigue damage produced by the whole truck, d_{ESAL} is the fatigue damage produced by the equivalent standard axle (130 kN axle), d_{Axle_i} is the damage produced by the i^{th} axle of the truck and n is the number of axles of the truck.

As shown in Figure 34 and Figure 35, the single tridem trailer axles produce the highest damage for the 5-axle semitrailer truck used. Considering a level of damage of 20 % of the pavement (corresponding to a typical service life for a medium-traffic pavement), the CA_{truck} values shown in Figure 34 indicate no clear difference between using vehicles in individual or platoon configuration in winter. The opposite effect occurs in summer, where the platoon configuration increases the CA_{truck} values for all the trucks. As the same figure shows, this effect can be considerably reduced (almost by a factor of 2) by increasing the wandering interval among the trucks (here from 20 cm to 40 cm). The figure also shows that the most aggressive axles are the rear tridem axles.

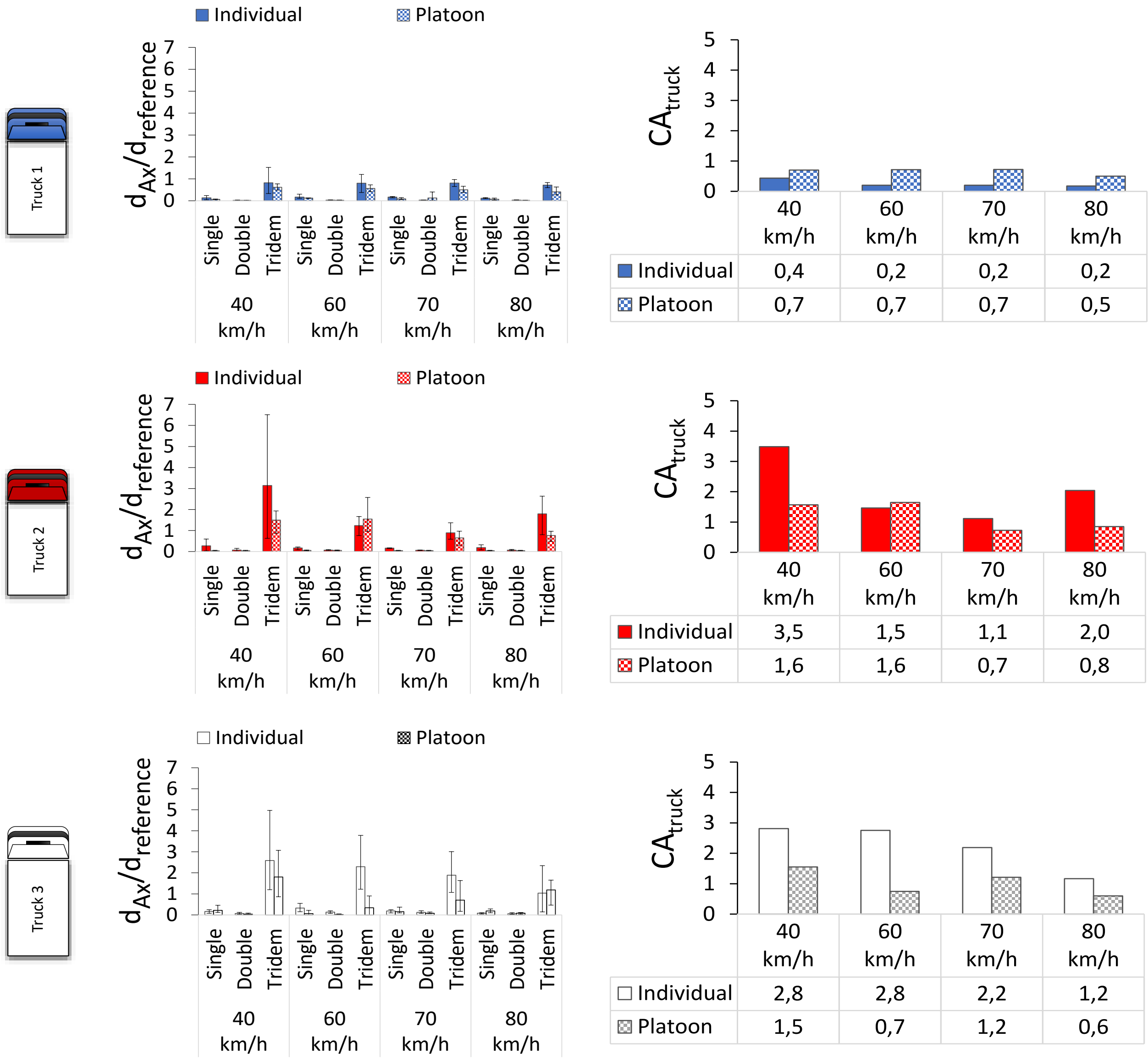


Figure 34: Values of fatigue damage induced by each truck axle (relatively to the reference 130 kN axle), and CA_{truck} values of the different trucks, for the winter test campaign.
Note: reprinted from (Paulina Leiva-Padilla et al., 2022).

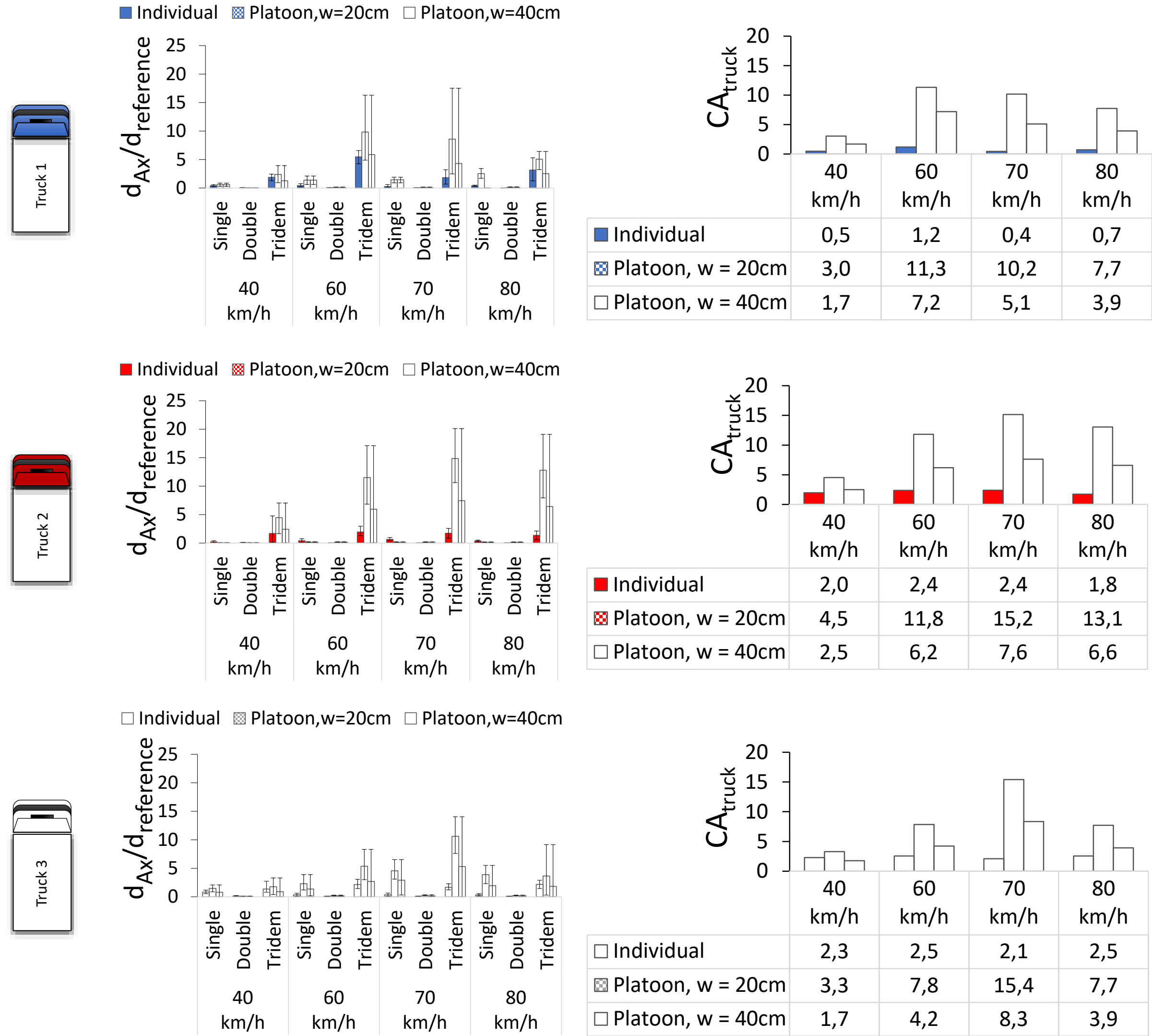


Figure 35: Values of fatigue damage per axle and CA_{truck} values for the summer campaign.
Note: reprinted from (Paulina Leiva-Padilla et al., 2022).

As shown in Figure 36, the CA_{truck} values obtained were finally used to determine the remaining fatigue life of the pavement test section of the study. According to the figure, compared to the reference scenario, using platoons in winter does not change the pavement fatigue life, while using them in summer or along the year can reduce this fatigue life considerably, with a maximum reduction of 63 % at 70 km/h. However, as demonstrated for Scenario 4, these values could be reduced by extending the wandering interval. In addition, controlling other parameters, like inter truck distances or maximum axle loads could also help reduce the impact of platoons on pavement fatigue.

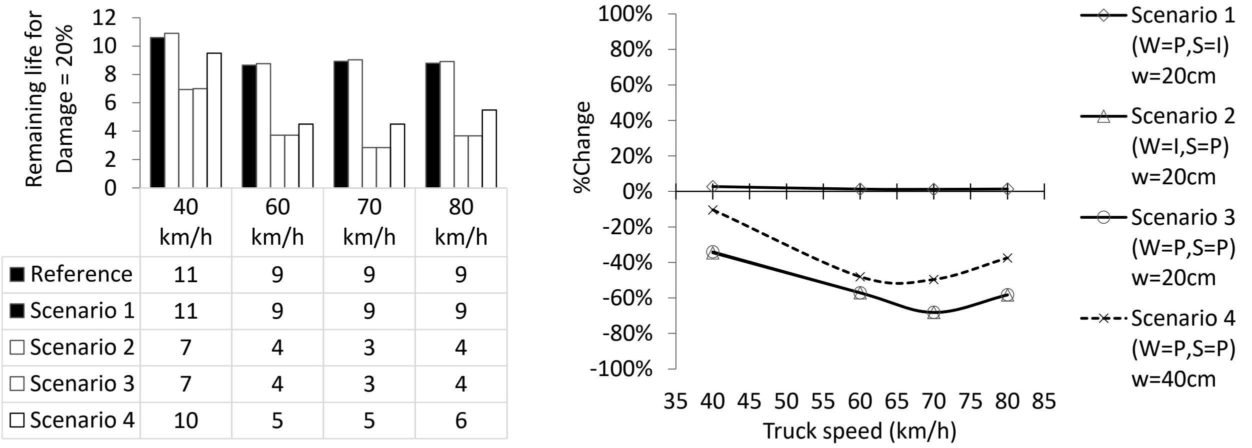


Figure 36: Calculated pavement fatigue lives, for 20% of damage, for different platoon traffic scenarios (W: winter, S: summer, I: individual, P: platoon).
Note: reprinted from (Paulina Leiva-Padilla et al., 2022).

3.2. Numerical modelling

This section presents successively three approaches, used in the project, for modelling pavement response under platoon loading:

- Approach 1. Preliminary model to analyse wandering patterns.
- Approach 2. Validation of a model based on full-scale tests.
- Approach 3. The effect of platoon characteristics on the fatigue life of pavements.

3.2.1. Approach 1. Preliminary model for simulation of wandering patterns

The first approach refers to numerical simulations to evaluate how wander patterns of platoons can influence pavement fatigue life. The numerical simulations done in this approach were based on the use of the software ViscoRoute 2.0 (Chabot et al., 2010), which is a semi-analytical software developed to model pavement response under moving wheel loads, considering elastic or viscoelastic pavement materials. The results presented in this subsection have been published in the paper:

- Optimization of Truck Platoon Wander Patterns Based on Thermo-Viscoelastic Simulations to Mitigate the Damage Effects on Road Structures. Published on 26 August 2020 in the Proceedings of the 6th Accelerated Pavement Testing Conference.

3.2.1.1. Model inputs

The road structure analysed in this paper was selected to characterise a typical European pavement. The structure used comprises 2 viscoelastic asphalt layers on an infinite elastic roadbed. A Poisson ratio of 0.35 is used for all the layers. The viscoelastic Huet-Sayegh parameters of the 2 asphalt layers are shown in Table 4. The surface course corresponds to a 2,5 cm thick layer of thin asphalt (BBTM) and the base course to a 20 cm thick layer of high modulus asphalt (EME). The subgrade was represented as an elastic material with a Young modulus of 120MPa.

	$E_0(MPa)$	$E_\infty(MPa)$	k	h	δ	A_0	A_1	A_2
Surface course (BBTM)	19	19644	0,213	0,628	2,535	3,072	-0,382	0,00165
Base course (EME)	22	31008	0,186	0,599	2,064	5,865	-0,388	0,0020

Note: Reprinted from (Marsac et al., 2020).

Table 4: Values of the Huet-Sayegh model parameters for the 2 asphalt materials.

Figure 37 shows the loading configuration selected to simulate a platoon configuration of 3 trucks with 2 m of inter-vehicular distance and several lateral deviations (d ranging from 0 to 35 cm with an incremental step of 5 cm) for trucks 2 and 3.

This first study was performed before the full-scale experiment, and therefore it was purely numerical, and based on generic pavement and material parameters.

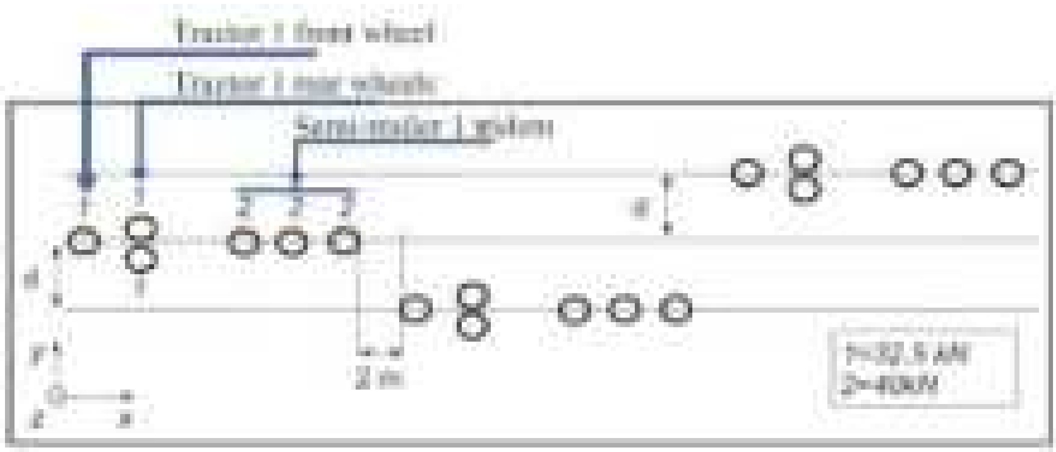


Figure 37: Loading configurations: platoon of 3 tractor/semi-trailer trucks with 2 m inter-vehicle distance and variable transversal distance d between the wheel paths of each truck
Note: Reprinted from (Marsac et al., 2020).

3.2.1.2. Results

The results are based on simulations done at 30°C (asphalt temperature). Figure 38 shows the envelopes of transverse strain profiles obtained for lateral deviations of 0 cm, 15 cm and 25 cm. As can be seen from the three curves, the close formation of the three vehicles in platoon leads to generate a strain accumulation, which is maximum for the condition with a lateral deviation equal to zero.

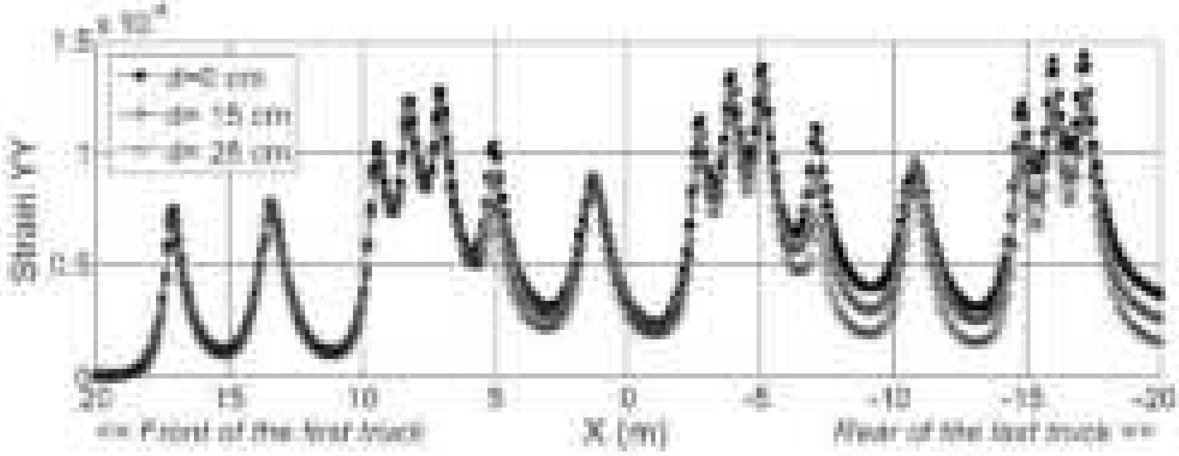


Figure 38: Envelopes (maximum value on a transverse profile) of the strain (eyy) along the longitudinal (x) axis for d = 0, 15 and 25 cm.
Note: Reprinted from (Marsac et al., 2020).

To understand this effect in terms of damage, a calculation using the software Alizé was made. According to the Alizé methodology (Balay, 2013), the damage D (Equation 3) of a platoon could be considered as proportional to the sum of the positive strain εyy peaks power the slope of the fatigue law.

$$D = K^{1/b}\left(\sum_{i=1}^{i=n}\varepsilon_{di}^{-1/b} - \sum_{i=1}^{i=n-1}\varepsilon_{uli,i+1}^{-1/b}\right) \quad \textbf{Equation 3}$$

Where, K: the constant of the fatigue law, $-1/b$: the slope of the fatigue law (in this study, a value of $-1/b$ = 5 is assumed), ε_{di}: the i order local peak of εyy on a longitudinal profile, $\varepsilon_{uli,i+1}$: the i order local inter-peaks minimum of εyy on a longitudinal profile.

Figure 39 shows the distribution of the calculated damage D (Equation 3) along with the transverse direction y. According to this figure a ratio of about 6 is obtained between the damage without wandering (which is concentrated in a very narrow zone) and the damage with a lateral deviation of d = 25 cm (which is distributed over a much larger area).

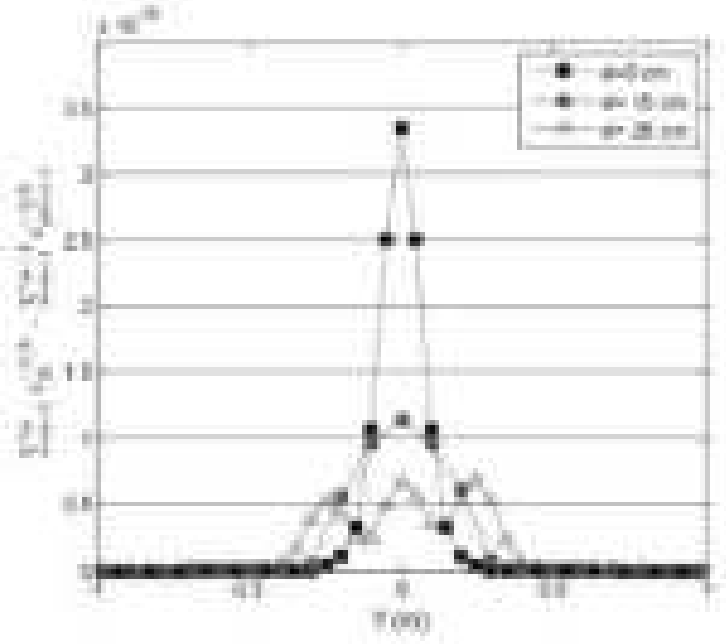


Figure 39: Second term of the right side of Equation 3, proportional to D, along the transverse direction.

Note: Reprinted from (Marsac et al., 2020).

3.2.2. Approach 2. Validation of a model base on full-scale tests

The second approach is related to the validation of a numerical model to simulate the strain values obtained from the full-scale experiment described in section 2. The model was developed again using ViscoRoute 2.0 (Chabot et al., 2010). The results shown in this subsection are part of the following paper:

- The Impact of Platooning Action on Asphalt Pavement: Monitoring on site (P. Leiva-Padilla, Blanc, Trichet, Baudru, et al., 2022). Paper accepted to be published in the Proceedings of the 11th International Conference on the Bearing Capacity of Roads, Railways and Airfields

3.2.2.1. Model inputs

Table 5 and Table 6 show the geometry and material properties used during modelling to represent the pavement structure of the test section described in Section 2. As both tables show, the viscoelastic behaviour of the asphalt layers was simulated using the Huet-Sayegh model. The interfaces between the asphalt layers were modelled as thin viscoelastic interlayers with typical Huet-Sayegh parameters of a tack coat emulsion. The unbound granular foundation was modelled as an elastic material with a modulus value of 180 MPa according to the typical values for the type of material present in the test section. Calculations were performed at temperatures corresponding to mean temperatures measured on site for each layer, during each test period.

Layer	Thickness (m)	Poisson ratio	Modulus (MPa)	Material behaviour	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
Binder course	0,060				11,3	6,1	25,9	27,0
Thin interlayer	0,002				11,3	6,1	25,9	27,0
Base course	0,150				10,3	8,3	27,5	27,7
Thin interlayer	0,002				10,3	8,3	27,5	27,7
Foundation	-	0,40	180 **	Elastic	-	-	-	-

Notes Table 1:

Reprinted from (P. Leiva-Padilla, Blanc, Trichet, Baudru, et al., 2022).

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

**Common value for a zahorra (Spanish denomination 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 5: Material properties and geometry used in the model.

Huet Sayegh*: Adjustment factor*:	$E^*(\omega,\tau) = E_0 + \frac{E_\infty - E_0}{1+\delta\left(i\omega\tau(\theta)\right)^{-k} + \left(i\omega\tau(\theta)\right)^{-h}}$ $\tau(\theta) = \exp\left(A_0 + A_1\theta + A_2\theta^2\right)$								
Layer	Material type	E_∞ (MPa)	E_0 (MPa)	δ	k	h	A_0	A_1	A_2
Wearing course	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
Viscoelastic interlayer	Tack coat ****	1968	0	9,048	0,272	0,883	-1,629	-0,391	0,002

Notes Table 2:

Reprinted from (P. Leiva-Padilla, Blanc, Trichet, Baudru, et al., 2022).

*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).

Table 6: Huet-Sayegh parameters at 15°C for viscoelastic characterization of the asphalt layers.

Each truck in individual and truck platoon configuration was represented by load areas similar to the ones described in Figure 40. As the figure shows, six rectangular areas, loaded by a uniform vertical pressure, were used to model the right half of each axle of the truck. The load area width corresponds to the tire width according to the type of tire used, 25,5 cm for the steer and drive axle and 28,5 cm for the trailer tridem axle.

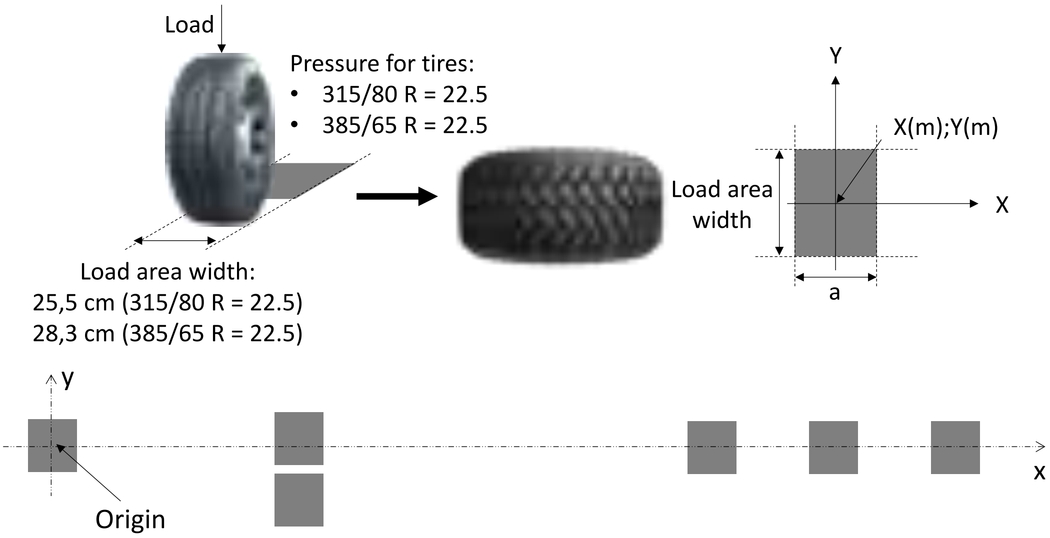


Figure 40: Load areas used during modelling (the images are not to scale).
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Baudru, et al., 2022).

3.2.2.2. Results

Figure 41, Figure 42, Figure 43 and Figure 44 show the transverse and longitudinal strain signals obtained from the strain gauges T1, T2, L1 and L2 installed in the test section and the corresponding values calculated with the software ViscoRoute. The values correspond to the pavement responses produced in the pavement when trucks pass in platoon configuration at 40 km/h and 80 km/h, for both winter and summer campaigns.

As both figures show, the model predicts accurately both the transverse and longitudinal signals obtained for both conditions. Additionally, it was possible to reproduce the higher strains associated with the higher temperatures present in summer. This means that the model represents well the real pavement performance under the platoon configurations applied, and therefore that it could be used to predict the pavement response for other load conditions, varying the parameters associated to the truck platoon: (1) multi-load configurations, (2) wandering and (3) inter-truck distances.

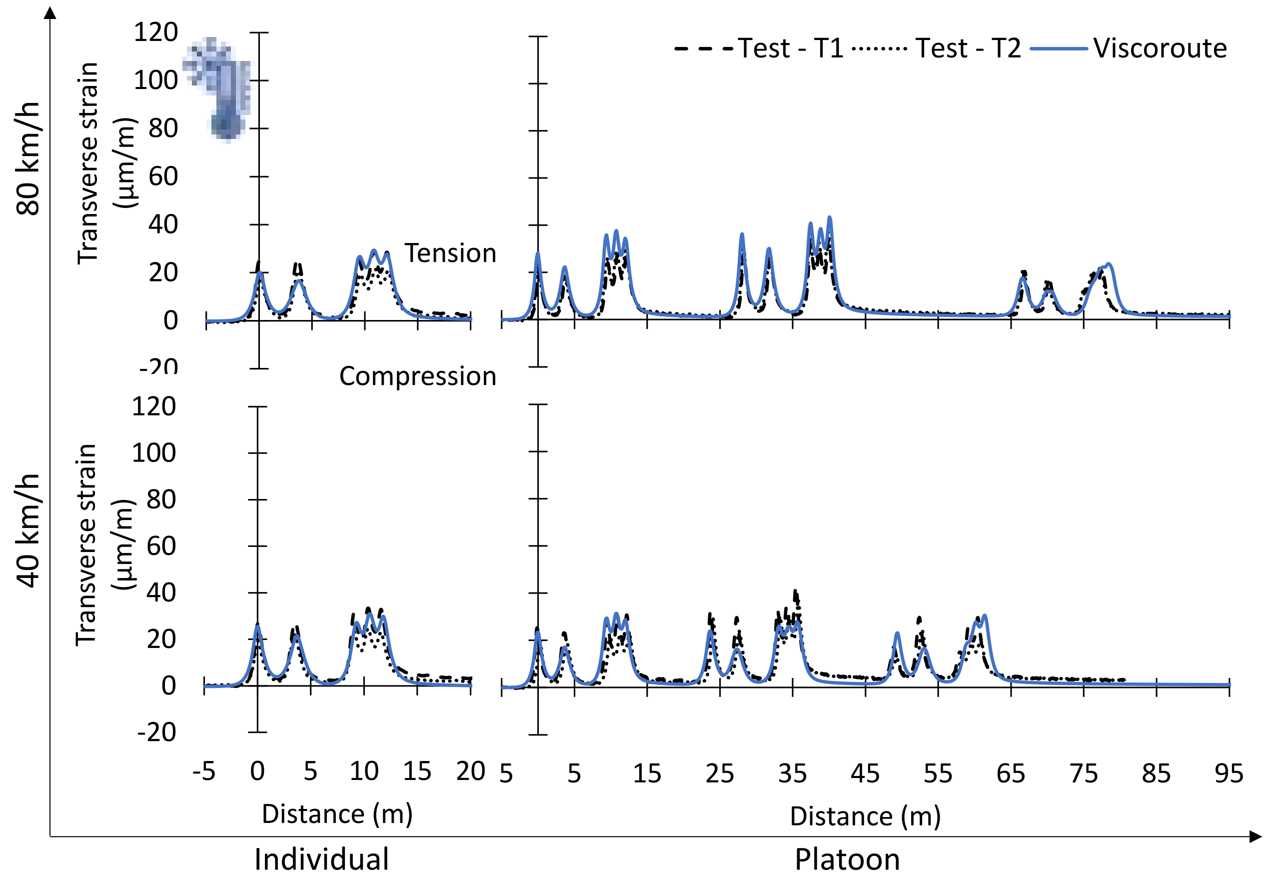


Figure 41: Measured and calculated transversal strains at the bottom of the subbase asphalt layer (winter campaign).

Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Baudru, et al., 2022).

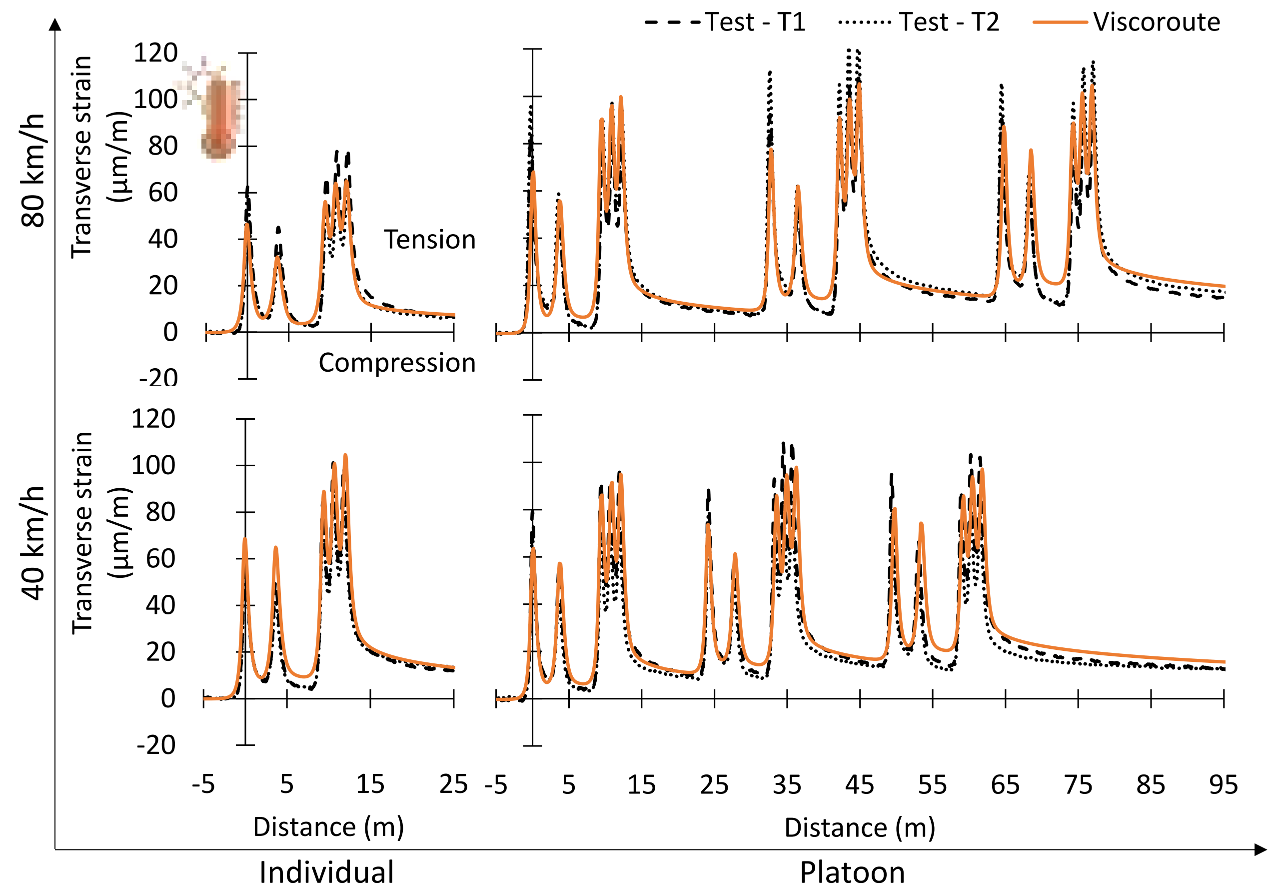


Figure 42: Measured and calculated transversal strains at the bottom of the subbase asphalt layer (summer campaign).

Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Baudru, et al., 2022).

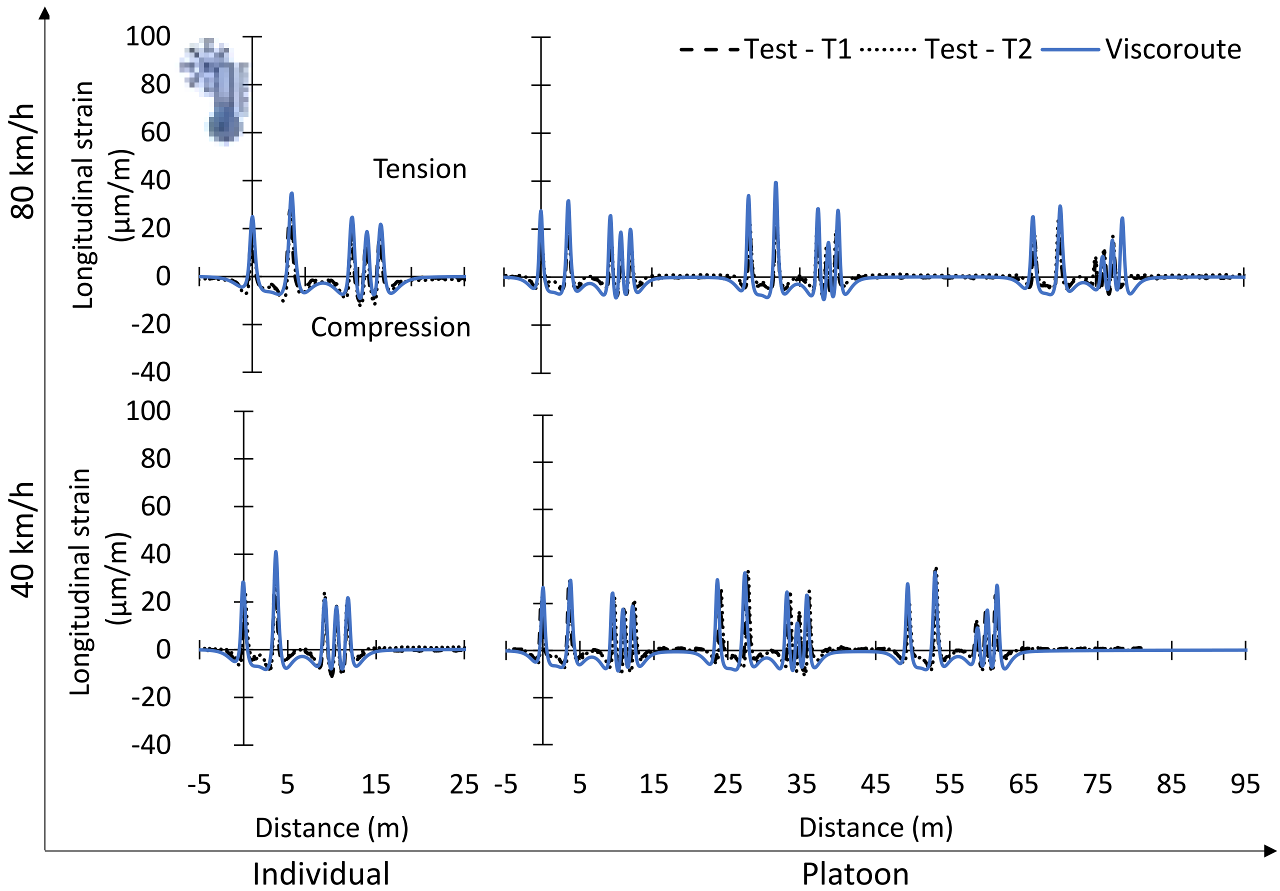


Figure 43: Measured and calculated longitudinal strains at the bottom of the subbase asphalt layer (winter campaign).

Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Baudru, et al., 2022).

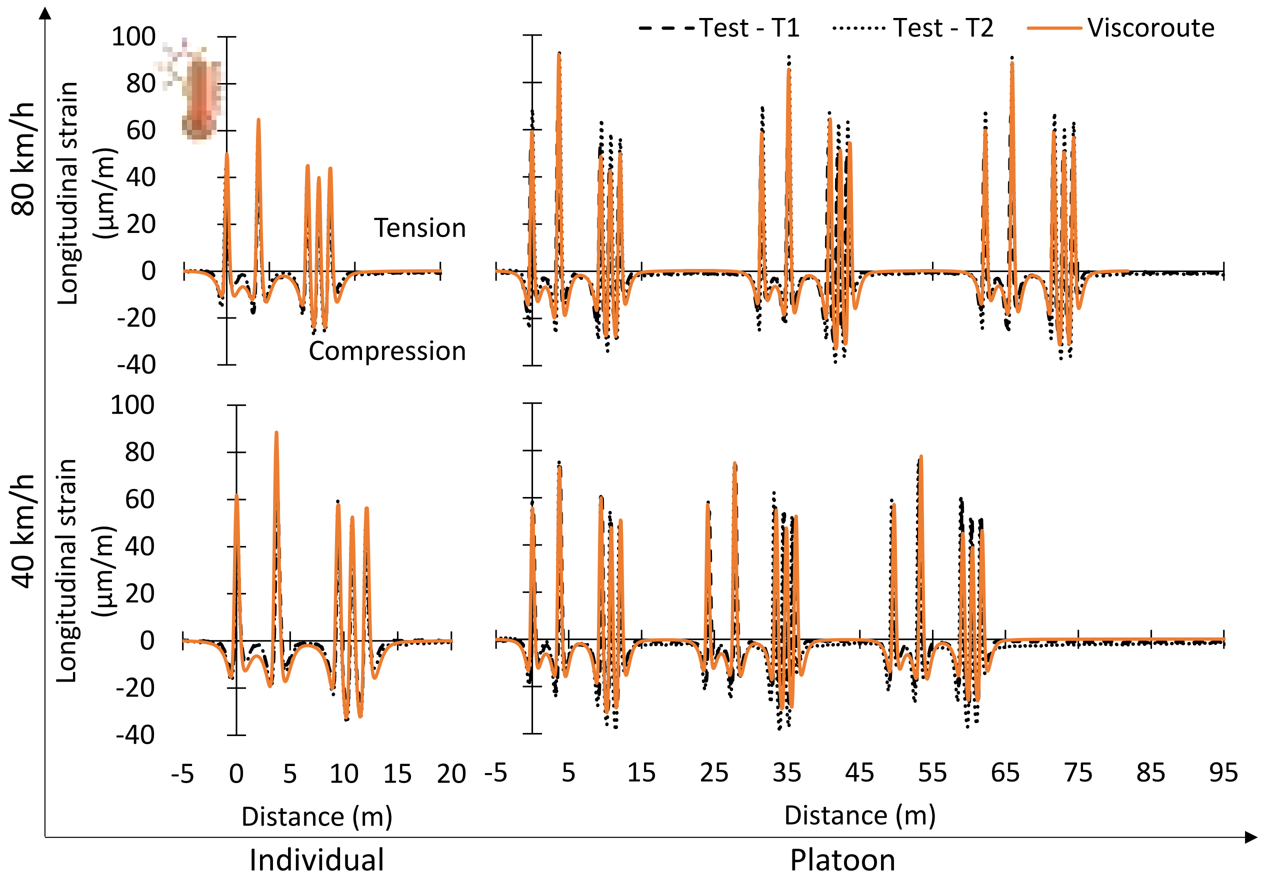


Figure 44: Measured and calculated longitudinal strains at the bottom of the subbase asphalt layer (summer campaign).

Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Baudru, et al., 2022).

A comparison between the maximum transverse and longitudinal strains obtained for each axle of each truck in both individual and platoon configurations and for both test campaigns is shown in Figure 45. The analysis of the linear relationships between both components reveals that the maximum strain values are higher in the transversal direction for the single wheel axles, which are the steer and trailer tridem. This means that changing the load distribution or changing from single to dual tires for the trailer tridem axle could reduce the effect of platooning trucks.

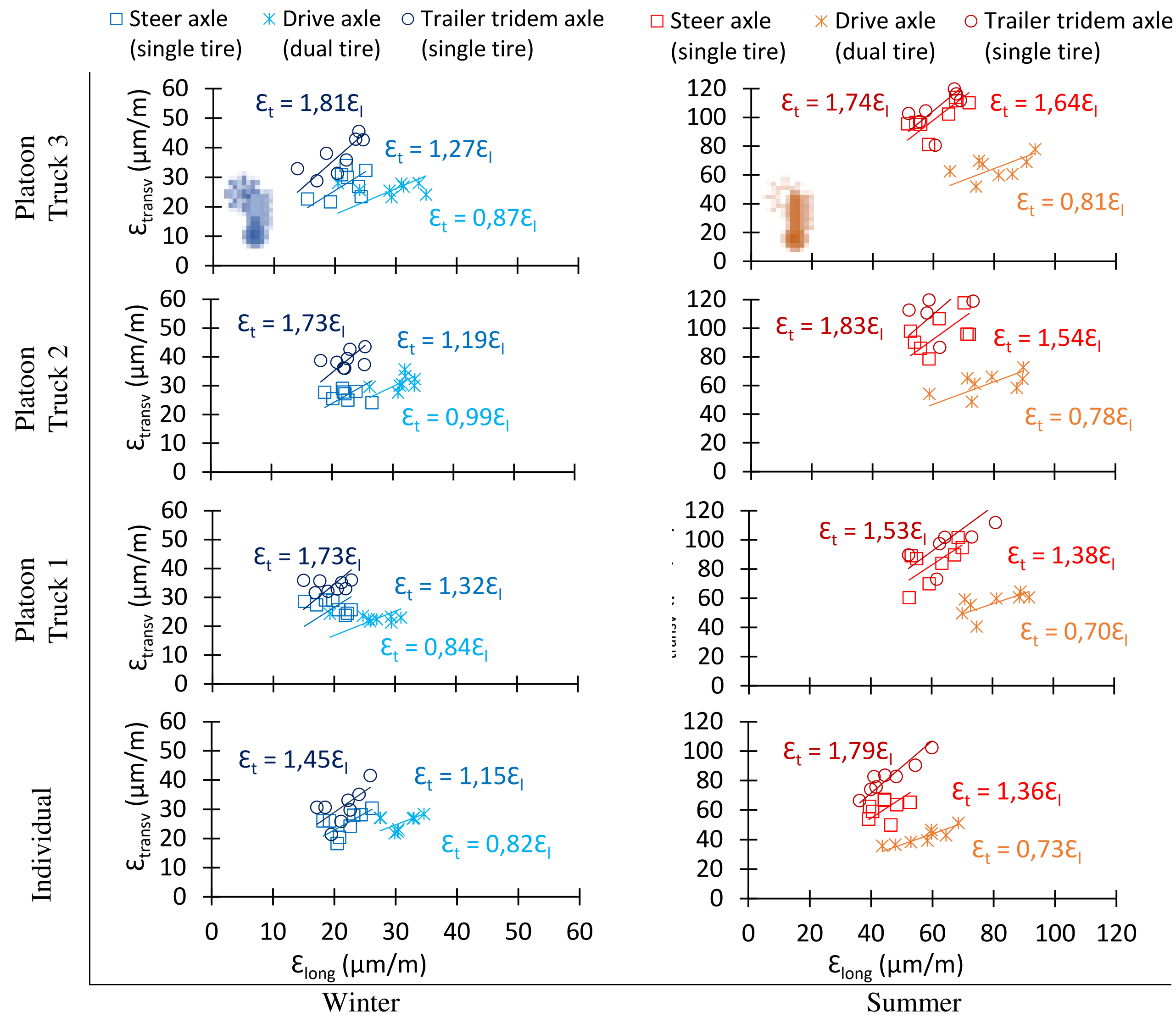


Figure 45: Comparison of the maximum transverse/longitudinal strains.
Note: reprinted from (P. Leiva-Padilla, Blanc, Trichet, Baudru, et al., 2022).

3.2.3. Approach 3. The effect of platoon characteristics on the fatigue strains of pavements

The third approach consists of the parametrisation of platoon configurations using as base the validated model described in Approach 2. The results shown in this subsection are part of the following documents:

- Evaluation of truck platooning on road structures in Europe. Paper submitted and under review to the International Society of Asphalt Pavements international conference 2022.
- The Impact of Platooning Action on Asphalt Pavements: A parametric study. Paper submitted to the International Journal of Pavement Engineering.

3.2.3.1. The effect of wandering and inter-truck time gaps

Using the validated model of Approach 2, equally dimensioned and loaded trucks were selected to analyse the effect of wandering and inter-truck time gaps. Figure 46 shows an example of the reduction in the transverse strain signals, at the same transversal position, that can be obtained at the bottom of the base course when a lateral deviation of ±30 cm (wandering of 60 cm) is included in a 3-truck platoon with inter-truck time gaps of 0.5 s. Figure 47 continues with the example showing how increasing the inter-truck time gaps can also help to reduce the transversal strains obtained.

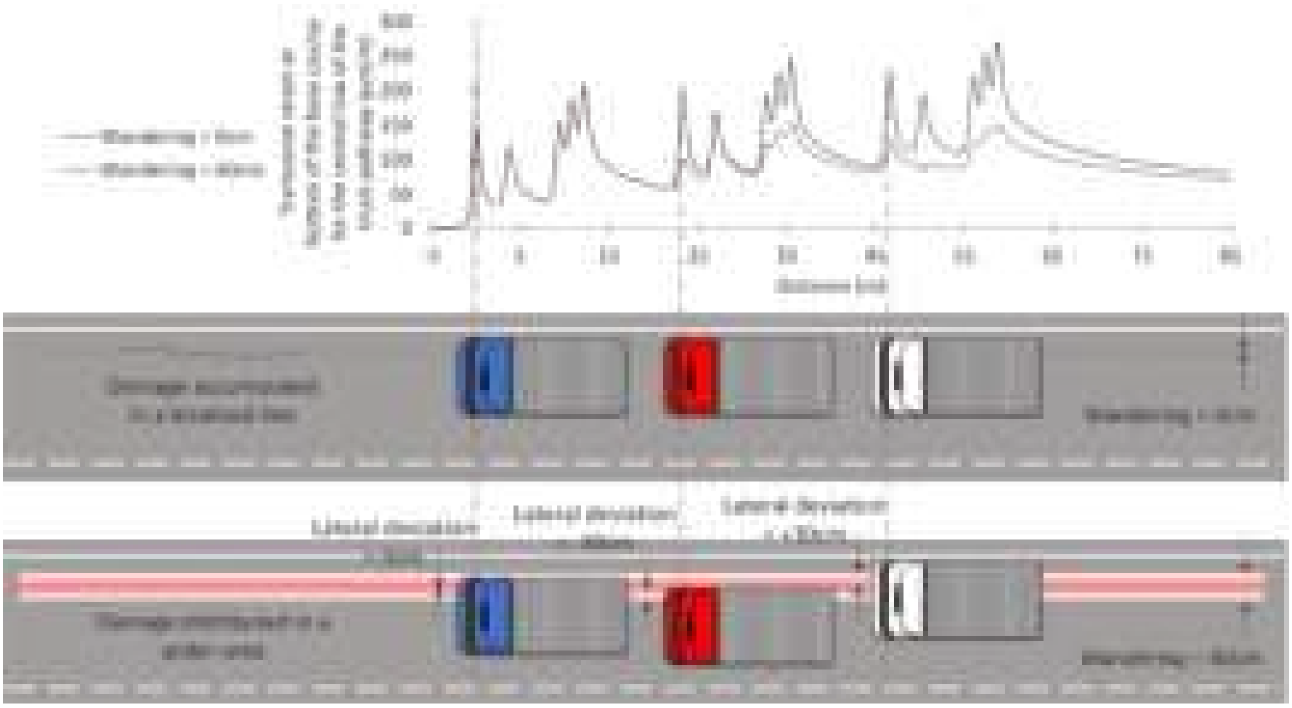


Figure 46: Example of wandering patterns among trucks in the platoon (truck speed = 80km/h, pavement temperature = 35°C, inter-truck time gap = 0.5 s, trailer tridem load = 40 kN per each tire).

Note: reprinted from (P. Leiva et al., 2022).

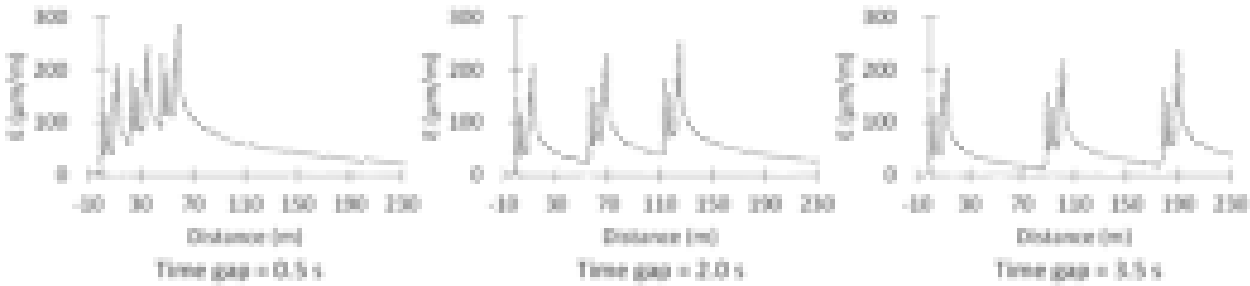


Figure 47: Example of inter-time time gaps among trucks (truck speed = 80km/h, pavement temperature = 35°C, inter-truck time gap = 0.5 s, trailer tridem load = 40 kN per each tire)

Note: reprinted from (P. Leiva et al., 2022).

Figure 48 and Figure 49 show the results obtained from also varying truck speed and pavement temperature. The values indicate that:

- Platooning trucks seem to have an effect on the maximum transverse strains mainly at high temperatures. For example, at 35°C, with zero lateral deviation and with a time-gap of 0.5 s the maximum strains increase 15% for truck 2 and 26% for truck 3 in comparison to truck 1. While at 15°C with zero lateral deviation and with a time-gap of 0.5 s, the maximum strain values increase only 2% for truck 2 and 4% for truck 3.

- In the case of the accumulated transverse strains obtained 0.5 s after the passage of each truck, platooning 3 trucks at 35°C and with zero lateral deviation means increasing by 54% and 92% the accumulated transversal strains for truck 2 and truck 3 in comparison to truck 1. At 15°C the percentages of increase are lower, with 35% and 55% for truck 2 and truck 3 in comparison to truck 1.

- Truck speeds also seem to have an effect on the transverse strains, especially at high temperatures. For example, at 35°C, passing from 40 km/h to 80 km/h means maximum transverse strains decrease by 20%, 23% and 24% for truck1, truck 2 and truck 3 with zero lateral deviation and 0.5 s of inter-truck time gaps. In the case of the accumulated transverse strains, the values increase by 64% and 71% for truck 2 and truck 3 in comparison to truck 1.

- As shown in Table 7, using platoons preferentially at low temperatures (winter and during early morning or night) can help to reduce the transversal strains obtained from platooning trucks. Also managing inter-truck time gaps, lateral deviation and truck speeds in the platoon could help to reduce the transverse strains obtained at high temperatures. **The results obtained in this case study are dependent on the pavement structure used in the analysis, the values could change for other conditions.**

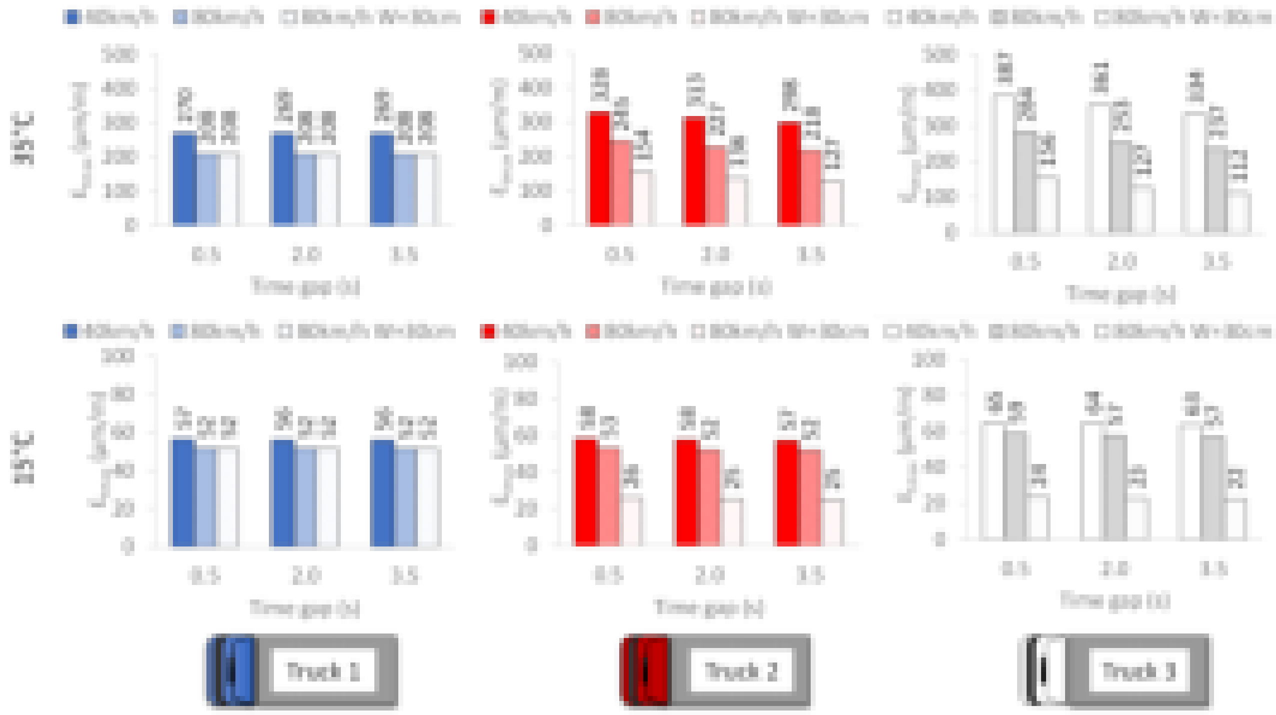


Figure 48: Maximum transverse strain obtained for the tridem trailer axle (trailer tridem load = 40 kN per each tire).

Note: reprinted from (P. Leiva et al., 2022).

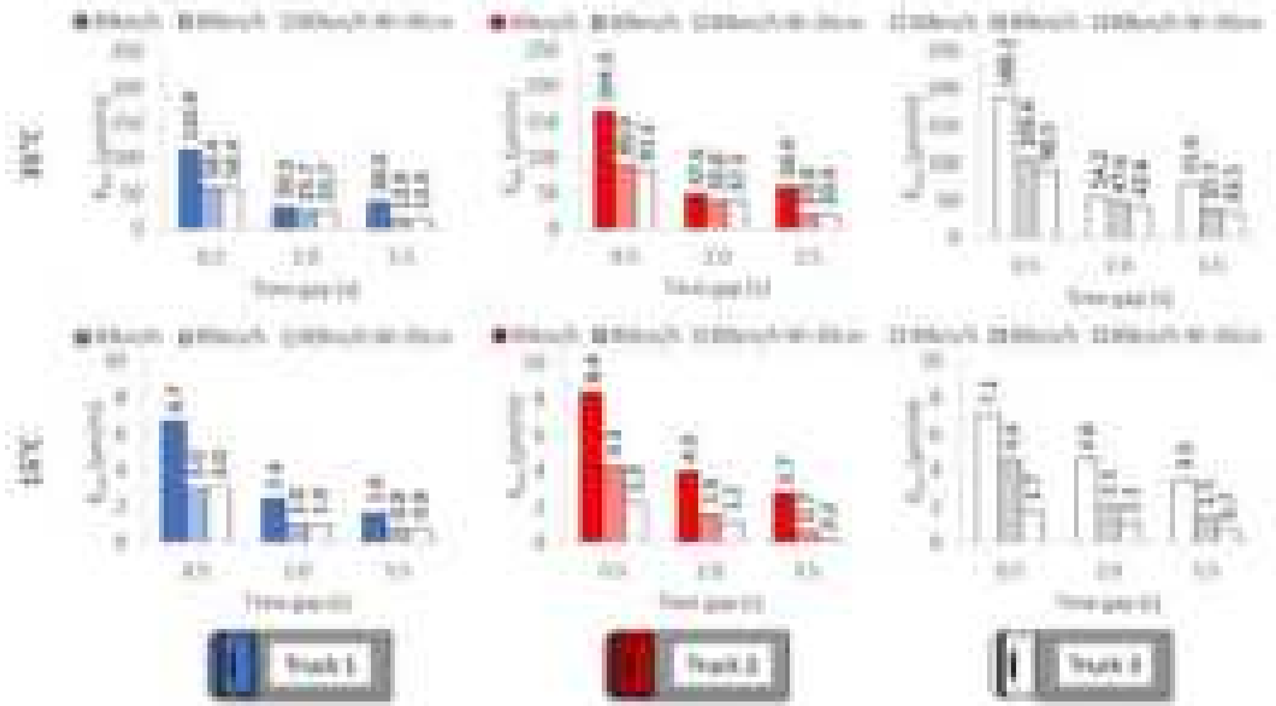


Figure 49: Accumulated transverse strain obtained after the pass of the tridem trailer axle (trailer tridem load = 40 kN per each tire).

Note: reprinted from (P. Leiva et al., 2022).

Parameter and management strategy proposed	Specific conditions	Strain reduction for the trailer tridem axle of truck 3 in the platoon	
		Maximum strain	Accumulated strain
Temperature = 35°C → 15 °C	Trailer tridem load = 40 kN Truck speed = 80 km/h Time gap = 0.5 s Wandering = 0 cm	73%	94%
Wandering = 0cm → 60 cm (±30 cm)	Trailer tridem load = 40 kN Truck speed = 80 km/h Pavement temperature = 35°C Time gap = 0.5 s	42%	12%
Inter-truck time gap = 0.5 → ı 3.5 s	Trailer tridem load = 40 kN Truck speed = 80 km/h Pavement temperature = 35°C Wandering = 0 cm	16%	65%
Truck speed = 40 km/h → 80 km/h	Trailer tridem load = 40 kN Wandering = 0 cm Pavement temperature = 35°C Time gap = 0.5 s	27%	50%

Table 7: Example of percentage of reduction in the maximum strain values obtained for the tridem trailer axle of a platoon composed of 3 trucks, by managing different loading parameters of the platoon.

3.2.3.2. The effect of the number of trucks and loads

Similar to the previous section, the effect of varying the number of trucks in the platoon and the load associated with the trailer tridem axle was evaluated. Figure 50 shows examples of transverse strain signals calculated for platoons of 3 to 7 trucks travelling at 40 km/h and with inter-truck time gaps of 0.5 s and loaded to 40 kN in their trailer tridem axle. The curves are compared with the ones calculated for the truck in individual configuration. For all the cases, it is possible to see that, platooning trucks reduces the rest time of the asphalt layers in the pavement, which produces an accumulation of transverse strains leading to higher maximum transverse strains in comparison to trucks in individual configuration. The higher the number of trucks in the platoon, the higher is the induced strain increase.

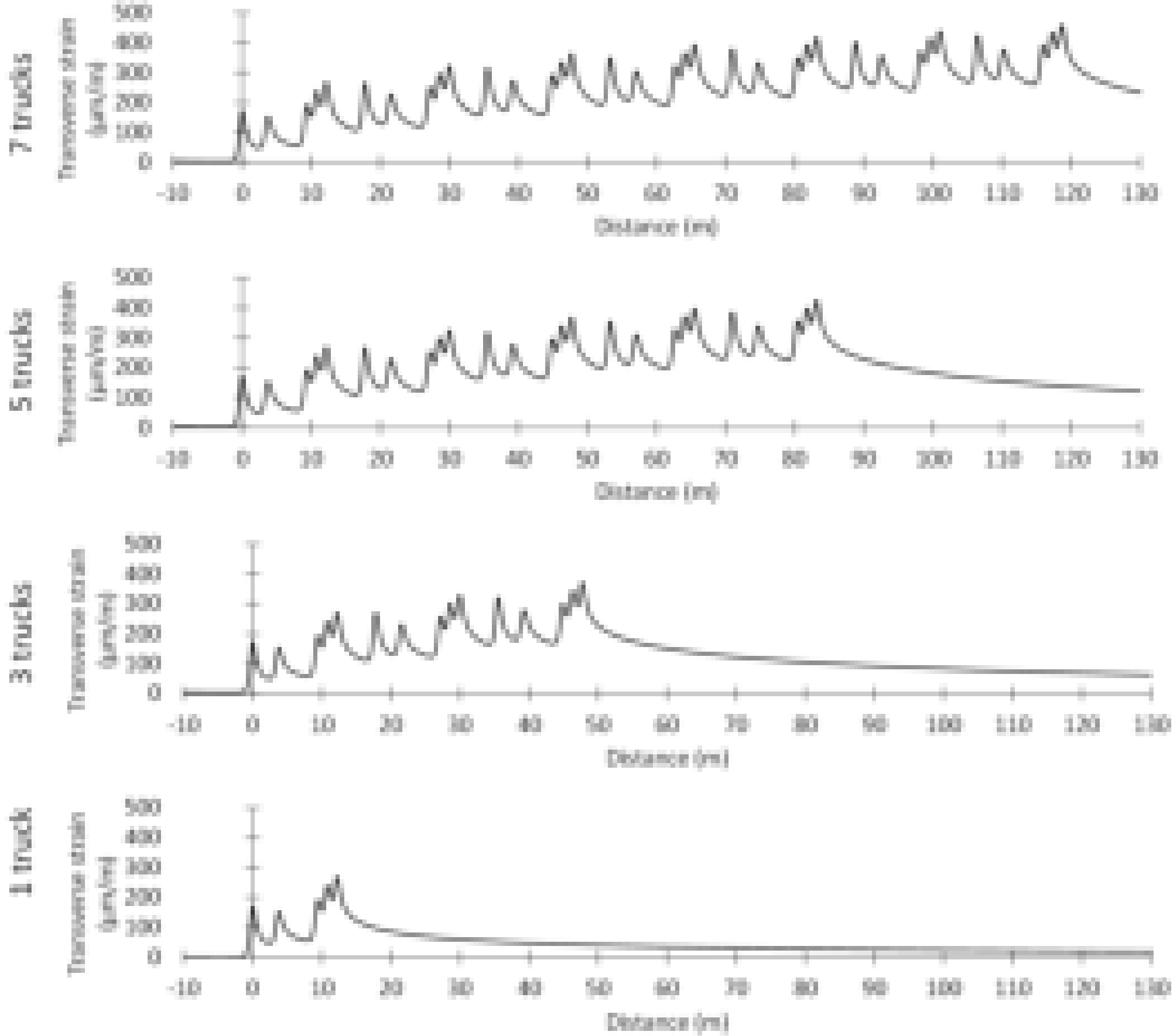


Figure 50: Example of transverse strain obtained by varying the number of trucks in platoon (truck speed = 40 km/h, trailer tridem load = 40 kN, inter-truck time gap = 0.5 s, temperature = 35°C, wandering = 0 m).

Note: reprinted from (P. Leiva et al., 2022).

Considering a reduction of the loads associated with the tridem trailer axle, which mostly receives the effect of the transported truck load, Figure 51 shows an example of the transverse strains calculated by decreasing the load per tire in the trailer tridem axle from 40.0 kN to 27.5 kN and 15.7 kN. As Figure 52 and Table 8 summarise, **for this example**:

- Platooning trucks increase the transverse strains at high temperatures (35°C for this example). This means for example that, to keep the same structural response of the pavement subjected to individual trucks loaded to 40 kN in the trailer tridem axle, a platoon with 3 trucks travelling at 40 km/h and with inter-truck time gaps of 0.5 s should reduce the loads of their trailer tridem axle tires to around 25 kN.

- At asphalt temperatures of 35°C, reducing the number of trucks in a platoon from 7 to 3 reduces the maximum and accumulated transversal strains generated by the platoon by 19% and 30%.

- At asphalt temperatures of 35°C, reducing the load per tire in the tridem trailer axle from 40 kN to 15.7 kN reduces the maximum and accumulated transverse strains generated by the platoon by 61% and 40%.

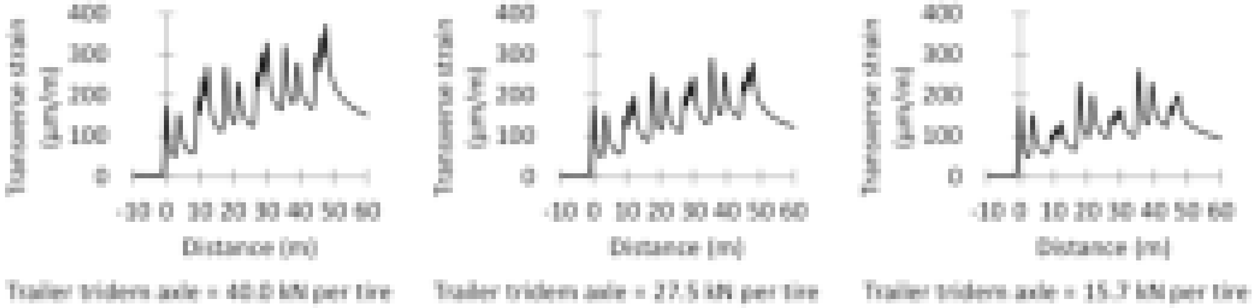


Figure 51: Example of transverse strains obtained by varying the load in the trailer tridem axle (truck speed = 40 km/h, wandering = 0 m, temperature = 35°C, inter-truck time gap = 0.5 s, 3-trucks platoon).

Note: reprinted from (P. Leiva et al., 2022).

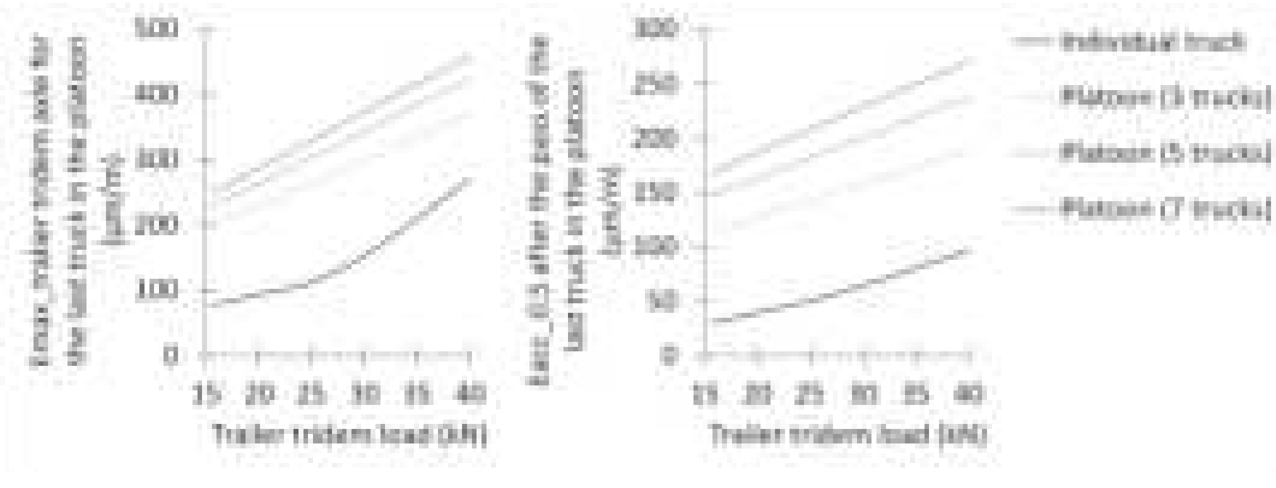


Figure 52: Maximum and accumulated transverse strains obtained by varying the load in the trailer tridem axle and the number of trucks in the platoon (truck speed = 40 km/h, wandering = 0 m, temperature = 35°C, inter-truck time gap = 0.5 s).

Note: reprinted from (P. Leiva et al., 2022).

Parameter and management strategy proposed	Specific conditions	Strain reduction for the trailer tridem axle of the last truck in the platoon	
		Maximum strain	Accumulated strain
Number of trucks = 7 → 3	Trailer tridem load = 40 kN Truck speed = 40 km/h Time gap = 0.5 s Wandering = 0 cm	19%	30%
Load per tire in the trailer tridem axle= 40kN → 27.5kN	Number of trucks = 3 Truck speed = 40 km/h Time gap = 0.5 s Wandering = 0 cm	31%	20%

Table 8: Example of percentage of reduction in the maximum strain values obtained for the tridem trailer axle of a platoon composed of 3 trucks, by managing different loading parameters of the platoon.

3.2.3.3. The effect of the asphalt layer thickness

As the previous section shows, platooning at high temperatures increases the maximum transversal strains in comparison to the ones obtained by individual trucks. Figure 53 shows the transversal strain values produced by varying the thickness of the base course in the pavement structure under study. As the figure shows, increasing the thickness provides a structure with a higher capacity to support the load solicitation of a platoon with 3 trucks.

Figure 54 shows that to produce the same transversal strain with a 3-trucks platoon (at 40 km/h and inter-truck time gaps of 0.5 s) and an individual truck in the current pavement structure with a base course of 0.15 m, it is necessary to increase the thickness of this layer to 0.25 m. This could mean an increase in the construction costs of the asphalt layers of the pavement in around 66%.

Considering that most of the pavement surface in Europe is already built with asphalt concrete materials, this could also mean requirement of quicker or more costly maintenance treatments to keep the same quality of service life of the pavement structures. A pavement in good condition reduces the dynamic movements of vehicles, which also reduces the costs associated with their maintenance and improves the quality of life of people that use them.

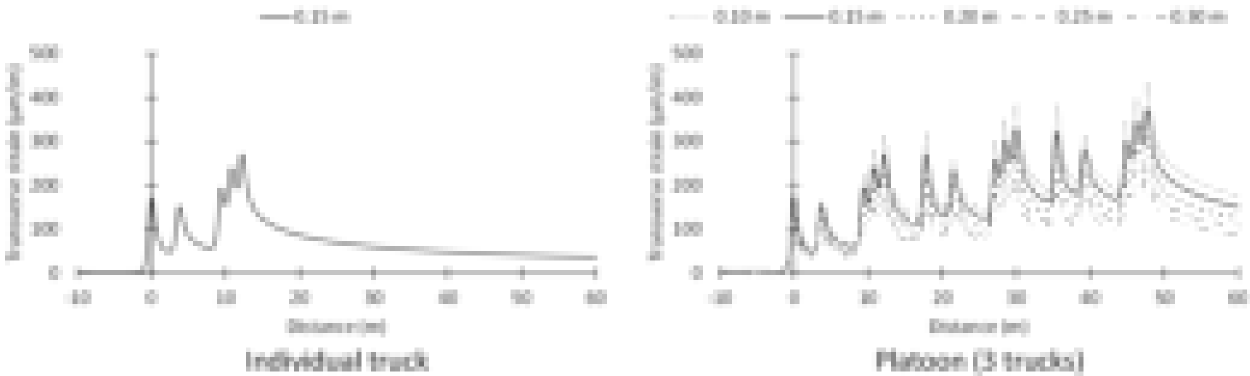


Figure 53: Transverse strains obtained by varying the thickness of the base course layer (truck speed = 40 km/h, wandering = 0 m, temperature = 35°C, inter-truck time gap = 0.5 s, trailer tridem truck load = 40 kN).

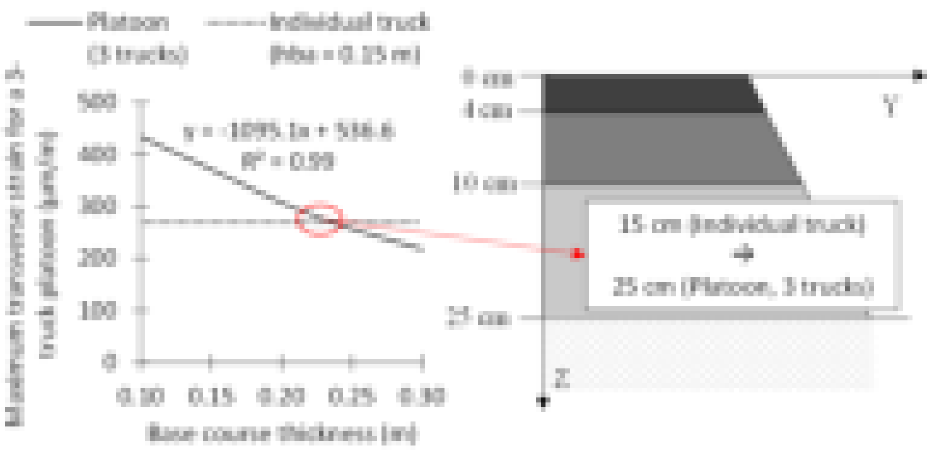


Figure 54: Change of thickness of the base course for the case study analysed in this report (truck speed = 40 km/h, wandering = 0 m, temperature = 35°C, inter-truck time gap = 0.5 s, trailer tridem truck load = 40 kN)

3.3. Documents produced to disseminate research results

As a product of the research efforts of the project, the documents and events shown in Table 9, allowed to disseminate the results obtained in Subtask 4.1.1. Impacts of platoons on pavements. A total of 3 journal papers and 5 communications in conferences were produced. .

Title	Document type	Disseminated through and state.
1. Optimization of Truck Platoon Wander Patterns Based on Thermo-Viscoelastic Simulations to Mitigate the Damage Effects on Road Structures (Marsac et al., 2020).	Conference paper.	Proceedings of the 6th Accelerated Pavement Testing Conference (APT2020). Published online: 26 August 2020.
2. Comparison of the response of an instrumented pavement section under individual and platoon truck loading (P. Leiva-Padilla, Blanc, Trichet, Salgado, et al., 2022).	Journal paper.	International Journal of Pavement Engineering. Published online: 22 Jan 2022.
3. Fatigue life predictions for a European pavement test section subjected to individual and platoon truck configurations (Paulina Leiva-Padilla et al., 2022).	Conference (poster session) /Journal paper.	101st TRB Annual Meeting. Transportation research record. Published online: 6 Jan 2022.
4. The Impact of Platooning Action on Asphalt Pavement: Monitoring on site (P. Leiva-Padilla, Blanc, Trichet, Baudru, et al., 2022).	Conference paper.	11th International Conference on the Bearing Capacity of Roads, Railways and Airfields (BCRRA). Accepted.
5. The Impact of Platooning Action on Asphalt Pavement: A parametric study.	Journal paper.	Under review in the International Journal of Pavement Engineering.
6. Evaluation of truck platooning on road structures in Europe.	Conference paper	ISAP Conference 2022. Submitted: 15 February 2022 Under review.
7. Evaluation of truck platooning on road structures in Europe (presentation based on results of papers 2 and 3).	Oral presentation. (Special invitation from the PIARC organising committee)	PIARC Conference 2022 (Calgary, Canada).
8. The Impact of Platooning Action on Asphalt Pavements: A parametric study (abstract based on paper 5).	Conference paper (Abstract accepted the 14 of march 2022, full paper in construction).	9th Transport Research Arena TRA Lisbon 2022, Portugal. Under review.

Table 9: Documents produced in the Subtask 4.1.1. Impacts of platoons on pavements.

4. SUBTASK 4.1.2: IMPACT ON BRIDGES

4.1. Problem statement

The issue of the introduction of multi brand platoons on bridges can be summarized in three studies:

4.1.1. Closer vertical loads

Even if convoys are being observed on European roads currently (Munduteguy, 2022), this practice is forbidden, and a 2-second gap is the minimum distance to be found between two vehicles.

The fact that platooning will bring the vertical axle loads closer, up to 0.3 s, will have an effect on long span bridges: for non-local effects with influence lines longer than 20 meters, more loads will have to be taken into account.

4.1.2. Aligned (in lateral position) vertical loads

Currently, a variability of the position of the trucks in the lane is observed in traffic measurements (X.-Y. Zhou et al., 2015), it is therefore expected and taken into account in the calculations (CEN, 2003). This is not the case for platooning as it is currently foreseen, where trucks would drive closer behind each other, in the same lateral positions, in order to maximize the aerodynamic drag and minimize fuel consumption.

This could be an issue for bridges with local, lateral localized effects: for example, for steel bridges with longitudinal stiffeners (for example, bridges with steel orthotropic decks), the fatigue life of some steel elements might be decreased a lot.

4.1.3. More, closer braking forces

The current design of bridges to horizontal forces is linked to the number of trucks on the bridge.

With platooning, at a given time, there might be more trucks on the bridge, meaning that the design loads might have a lower safety margin when compared to actual braking forces developed by platoons on a bridge.

On the other hand, platooning and CACC may reduce the brake forces as vehicles can better anticipate on the behaviour of the preceding vehicle. The shock-wave damping / string-stability CACC offers avoids late braking and therefore large brake force amplitudes.

4.2. Warning

The dynamic issues linked to platooning trucks will not be studied in this report, both in terms of dynamic amplification factor and complete dynamic simulation.

- The dynamic amplification factor (DAF) is the numerical tool used in the Eurocodes to account for the dynamic effects of trucks on bridges. While it would increase the calculated effects, it is not completely useful here as we mainly compare the effects of traffic with and without platoons, and therefore multiplying everything by the DAF would not change the conclusions

- A complete dynamic simulation of platoons on a bridge would make it necessary to model the trucks by a series of masses and springs. While this work is interesting and would lead to useful results, it has not been foreseen in the frame of WP4.1 of the ENSEMBLE project.

4.3. Methodology

The work will be carried out by calculating the effects of traffic loads, and compare these effects for traffic with platoons with the ones of traffic without platoons.

4.3.1. Assessment of effect of axle loads on bridges

Univ Eiffel has developed a tool which makes it possible to assess the effects of traffic loads on bridges.

The effects themselves are calculated through the convolution of the effect to be considered, with the vertical, moving axle loads of the traffic: this leads to the time series of effects (strains, stresses, …) in the bridges due to the traffic loads.

The effect on a moving load is given by the convolution of the moving load with the influence line of the effect. In particular, a moving vehicle with N axles would be considered as N moving loads, with given axle loads and given distance between the axles.
If $I_i(x)$ is the value of the influence line of effect i at coordinate x and we consider truck j, the global effect at coordinate x, $E_i(x)$, is given by the sum of the effects of all axles:

$$E_{i,j}(x) = \sum_{n=1}^{N} P_{j,n} I_i\left(x - d_{j,n}\right),$$

Where:

- $P_{j,n}$ is the axle load on axle n of truck j,
- $d_{j,n}$ is the distance between axle 1 and axle n for truck j (so by definition, $d_{j,1} = 0$).

The values of $P_{j,n}$ and $d_{j,n}$ are given by the vehicle configurations and the function $I_i(x)$ is representative of the chosen infrastructure.
This time series is then studied in terms of fatigue and extreme loads.

4.3.2. Assessment of extreme loads

By computing this effect $E_{i,j}(x)$, its maximum value can be assessed for the various traffic configurations. Two traffic configurations can then be compared in terms of extreme effects by calculating the ratio of the effect $E_{i,j}(x)$.

More precisely, in this work where we compare the “new” traffic with platoons to the current traffic (as measured), this means that the ratio of interest will be for each vehicle:

$$R_{i,j} = \frac{E_{i,j}}{E_{i,ref}},$$

Where:

- $R_{i,j}$ depends on the type of effect i and the vehicle j,
- $E_{i,j}$ is the maximum effect i of vehicle j,
- $E_{i,ref}$ is the maximum effect i of the reference vehicle (40t conventional trailer).

One can notice that by definition, for all effects, $\forall i$, $R_{i,ref} = 1$.

When comparing traffics, for example a measured traffic and a traffic where platoons have been introduced, more advanced extrapolation methods exist. These methods have been developed in the domain of the Extreme Value Theory, and have all their own advantages, drawbacks and accuracy (OBrien et al., 2015). The tool that has been developed makes it possible to apply easily GEV, GPD and Rice method on the same traffic loadings, and therefore to verify our results.

4.3.3. Fatigue assessment

Fatigue is a well-known issue for steel bridges, or steel elements in composite bridges. It is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. Therefore, it is linked to the GVW of the vehicles, but also the axle loads.

The fatigue life of the structure is given by the stress cycles exerted by the moving load on the structure. The aggressivity of the vehicle configurations is given by the following equations, that correspond to the S-N Wöhler curves (see **Figure 55**):

$$\begin{cases} N \times \Delta\sigma^3 = 5.10^6 \Delta\sigma_D^3 \; if \; \Delta\sigma \geq \Delta\sigma_D \,, \\ N \times \Delta\sigma^5 = 5.10^6 \Delta\sigma_D^5 \; if \; \Delta\sigma_D > \Delta\sigma \geq \Delta\sigma_L \,, \\ N = \infty \; if \; \Delta\sigma < \Delta\sigma_L \,, \end{cases}$$

Where:

- $\Delta\sigma$ is the stress cycle exerted by the moving load (vehicle) on the chosen infrastructure,
- $\Delta\sigma_L$ is the fatigue limit (depends of the material of the structure and given in Eurocode 3 and standards),
- $\Delta\sigma_D$ is the endurance limit (depends of the material of the structure).

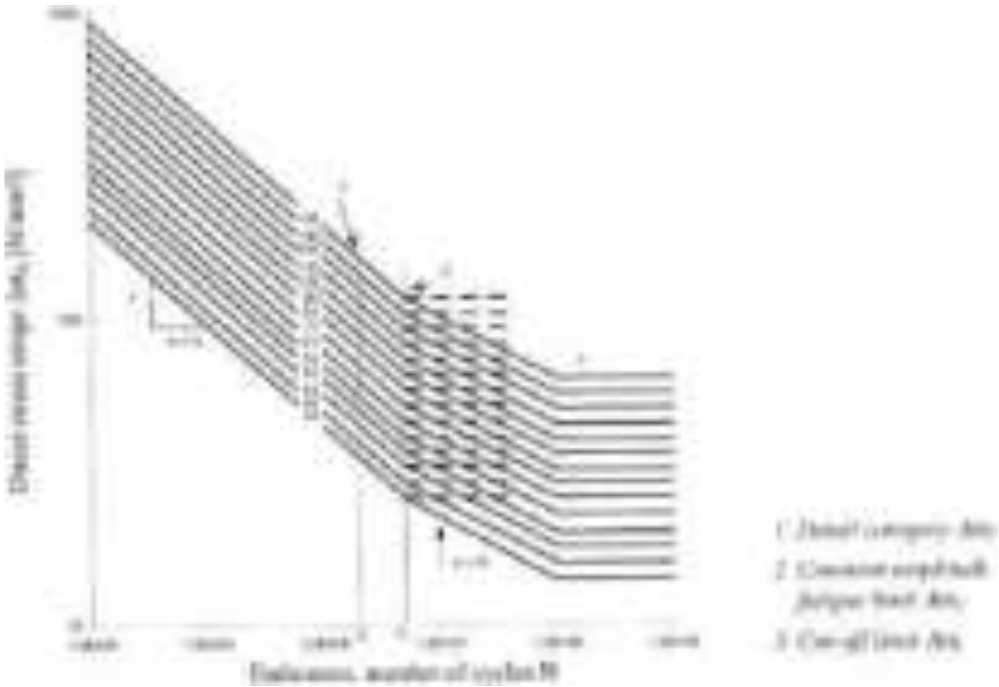


Figure 55: S-N Wöhler curves (extracted for (CEN, 2005)**)**

The fatigue life is then calculated using Miner's law, by reducing the complex loading (of variable amplitude) to a series of simple cyclic loadings (histogram of cyclic stress).

The damage d is linearly cumulative: For a single cycle (σ) damage, d is equal to $1/N_R$, where N_R is the number of cycles and there is failure when $d = 1$.

For N_i cycles of amplitude σ_i: $d_i = {}^{N_i}/_{N_{Ri}}$, therefore for all cycles: $d = \sum d_i = \sum \frac{N_i}{N_{Ri}}$.

This makes it possible to assess the fatigue life of a structure based on the time series of the effects, calculated or measured.

4.3.4. Comparison of effects

The conclusions in this report will be based on comparisons between the estimated effects of traffic as it is currently (measured or complying with the regulations), and traffic where platoons have been introduced. The effects that will be studied are chosen and explained in each part of the work, depending of the issue to be considered (longitudinal gaps, lateral position in the lane, horizontal forces).

Two types of comparisons will be done, by comparing individual trucks/series and trucks, and comparing traffic files:

Truck/series of trucks:

a. Trucks alone: as for the pavement impact assessment, we define a fully loaded, an average loaded, an empty truck (see Table 10). These trucks are of type 5-axle semi-trailer (2-axle truck followed by a 3-axle semi-trailer, where the tridem is located at the end of the trailer).

Truck type	Number axles	Weight on axles (kN)					Distance from 1st axle (cm)				
		Axle 1	Axle 2	Axle 3	Axle 4	Axle 5	Axle 1	Axle 2	Axle 3	Axle 4	Axle 5
Fully loaded	5	100	115	90	90	90	0	370	940	1080	1220
Average loaded	5	100	115	62	62	62					
Empty	5	100	115	35	35	35					

Table 10: Definition of a fully loaded, an average loaded, an empty truck.

This truck configuration has been studied within the ENSEMBLE project, because this type of truck is common in Europe, as it represents 60 % of European trucks and 75 % of French ones (F. Schmidt et al., 2016).

b. Platoons of 2, 3, 4, .., ,7 trucks at various time gaps (0.3 s, 0.4 s, 0.5 s, 0.7 s, 0.9 s, 1.2 s, 2 s, 3 s).

To define these series of trucks, the distance between trucks had to be defined: indeed, when talking about the gap between trucks, OEMs and other truck specialists consider the distance between the rear bumper of the truck in front to the front bumper of the truck driving behind.
On the other side, when discussing the distance between trucks, bridge engineers (and in general civil engineers) deal with the distance between the last axle of the preceding truck and the first axle of the following truck.
Therefore,

$$distance\ between\ trucks = d_{5,i-1} + gap + d_{0,i},$$

Where:

- Distance between trucks is the distance as used by civil engineers, for pavement and bridge impact assessment,
- $d_{5,i-1}$ is the distance between the last axle of the preceding truck and its rear bumper. For the vehicles tested in ENSEMBLE (semi-trailer with a tridem towards the rear of the trailer), this distance can be found to be approximately equal to 2,92 m (for example by consulting the design of well-known trailers),
- gap is the distance between trucks as measured (generally in seconds) between the end of the bumper of the preceding truck and the front bumper of the following truck,

- $d_{0,i}$ is the distance between the front bumper and the first axle of the following truck. This distance is measured by WIM sensors. Looking at WIM databases (F. Schmidt et al., 2016), it is found that this length is between 115 cm and 160 cm for trucks of semi-trailers of type T2S3 (2-axle truck with tridem trailer), with a mean around 145 cm which is the value we will use in the following.

Complete traffic files:

c. Traffic as measured by Weigh-in-Motion stations: we use a complete year on traffic, as measured on three locations in France (a highway with dense and heavy traffic, a highway with lighter traffic, and a national road “Route Nationale” with heavy trafic),

d. Traffic modified to introduce platoons: to do that, we used the traffic files from 2.a. and by choosing penetration rates, trucks have been chosen randomly and gathered in platoons. To do that, their descriptions in terms of loadings (GVW, axle loads) and dimensions (distances between axles) have been kept the same, only the dates of passage have been changed.

4.4. Literature review, state-of-the-art

As stated in (Sayed et al., 2020), there is not much literature about the impact of platoons on bridge preservation. The findings already available in the literature deal with the impact of closer vertical loads and the increased braking forces.

Taking into account the vertical forces, static calculations show that for some types of bridges, the loads on both the superstructure and the substructure will be increased (see Figure 56). This increase in effect in bridges might lead to loads higher than the notional live loads (see Figure 57).

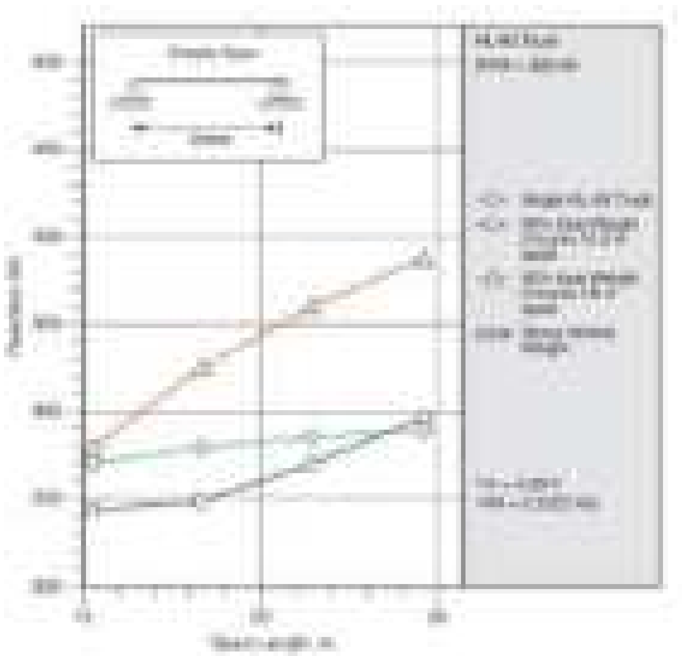


Figure 56: Reaction forces for a simply supported span, and various truck configurations. Extracted from (Sayed et al., 2020)**.**

In particular, as has been studied in (Tohme & Yarnold, 2020; Yarnold & Weidner, 2019), the effects by truck platoons might exceed the design loads, which brings about the need to verify the load models, and maybe calibrate again these loads models. In the USA, this would mean to work on the (Federal) Bridge Formula, while in Europe this poses the question of the calibration of the load models and/or the partial safety factors.

These changes would have to reflect the fact that the introduction of multi-brand truck platooning will bring about new load patterns.

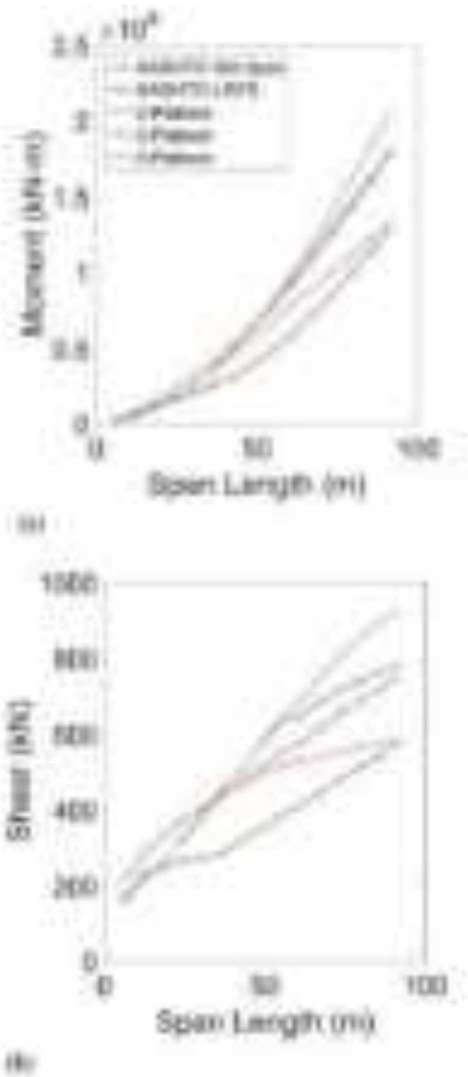


Figure 57: Simple span results of 6.1-m platoon for (a) positive bending; and (b) shear force. Extracted from (Yarnold & Weidner, 2019)**.**

Braking forces of platoons have also been identified as potential issues (Zhao & Uddin, 2013), and have been simulated through a complete truck-bridge modelling procedure. It has been shown that the number of trucks within a platoon, here again, is a key parameter to determine the aggressivity of the traffic.

Moreover, this type of design method is valid for new structures, but it does not deal with the issue of older, existing structures (Kamranian, 2018) whose structural health is unknown and which have already problems to cope with current traffic loadings.

Therefore many truck parameters have an influence of the potential impact of platoons on bridges, namely the number of trucks, the gap between them, the driving speed, … This shows the need of developments of regulations and advice for trucks operators, logistics and service providers. These studies on the impact of platooning on bridges would need to be done soon, as there is an inevitability of truck platooning (and/or semi-automated driving).

4.5. Impact of the reduced longitudinal gaps between axle loads

While convoys practice can be observed (Munduteguy, 2022), regulations state a minimum of 2-second in terms of gaps between the trucks.

Therefore the first step is to compare the effects of the individual trucks (fully loaded, average loaded, empty) with series (platoons) of the same trucks, at various time gaps. To do this, the effects to be considered have to be chosen.

4.5.1. Choice of effects for the longitudinal issue

The introduction of platoons in the traffic will not have an impact on effects with influence lines longer than the vehicle length, namely around 16.50m – 18.75m.

A set of 19 influence lines have been chosen, see Table 11.

Longitudinal influence lines	Influence line length
A : Moment on central support of a continuous beam of two simply supported spans	L = 25, 50, 100, 150, 200 meters
B : Total support reaction of a simply supported span	L = 25, 50, 100, 150, 200 meters
C : Maximum bending moment at mid-span of a simply supported span	L= 25, 50, 100, 150, 200 meters
D : Bending moment on support of a bi-fixed beam with variable inertia	L = 25, 50, 100, 150, 200 meters
E : Shear force at mid-span of a simply supported span	L = 25, 50, 100, 150, 200 meters
F : Additional thrust in the supporting cables for long deck lengths	L = 100, 150, 200 meters

Table 11: Choice of longitudinal influence lines.

4.5.2. Increase of traffic aggressivity due to decreased gap

Using these combinations of influence lines and trucks/convoys of trucks, many graphics showing the influence the multi brand platooning on bridges can be plotted (see Figure 58).

But some general conclusions can be drawn:

- If the length of the influence line is longer, the increase in aggressivity of the traffic on this effect will be higher. In particular, if the convoy/platoon is composed of more than 2 trucks, this will have to be calculated. On the other side, for a span length of 25 meters, there is no need to consider more than 2 trucks (and even this case is only interesting in the case of very small gaps between trucks).

- The increase of aggressivity will be maximal for the longer influence lines, especially those linked to the supporting cables of suspended bridges (type F). This is especially negative for older cable-stayed bridges, which already have issues to carry the current traffic loadings. The bridges with limitations in terms of acceptable GVW are generally not part of highway (more of secondary roads), so there should be no safety issues. Nevertheless, for older cable-stayed bridges on highway, a site-specific assessment would have to be performed.

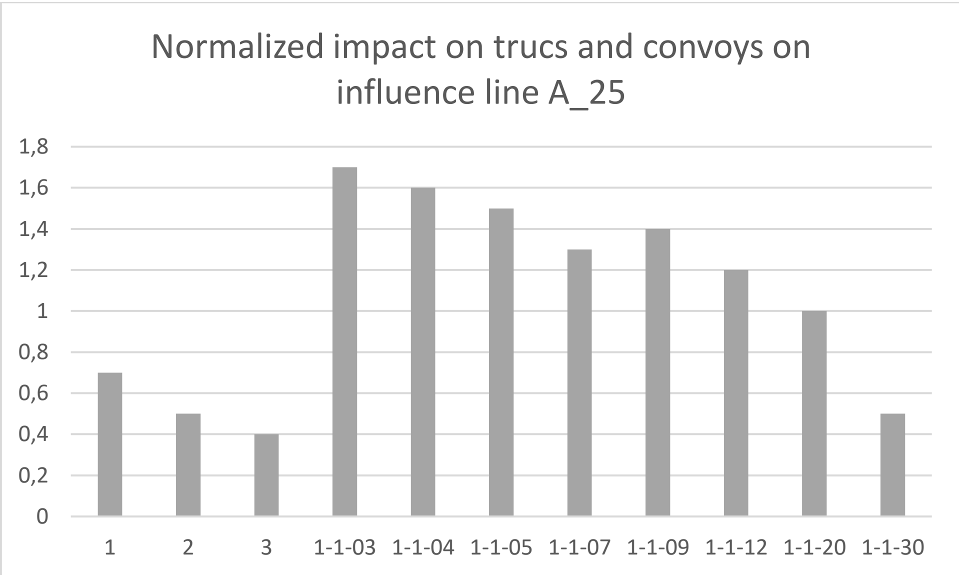


Figure 58: Normalized effect of trucks 1, 2 and 3, and convoys of trucks 1 (gap between 0.3 s and 3.0 s) on influence line A of length 25 m.

4.6. Impact of reduced lateral wandering

Eurocode 1 (CEN, 2003) proposes a statistical distribution for the position of the trucks in the lane (see Figure 59), but this might be changed for current traffic (see (X.-Y. Zhou et al., 2015) for example). This issue will be increased if trucks have lateral control.

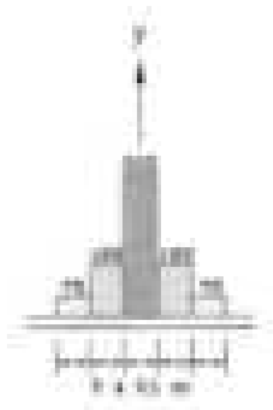


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Figure 59: Frequency distribution of transverse location, Figure 4.6 from (CEN, 2003)**.**

4.6.1. Choice of influence lines to be considered

Bridges sensible to this lateral issue are those with short, lateral influence lines, as for example bridges with lateral stiffeners. To assess the effect, we use here the influence lines of a bridge with orthotropic deck, as they have been measured directly with strain gauges (Jacob & Schmidt, 2019), see Figure 60.

For that, the strains at different lateral locations in the deck have been recorded during the passage a truck, which made it possible to assess the corresponding influence lines.

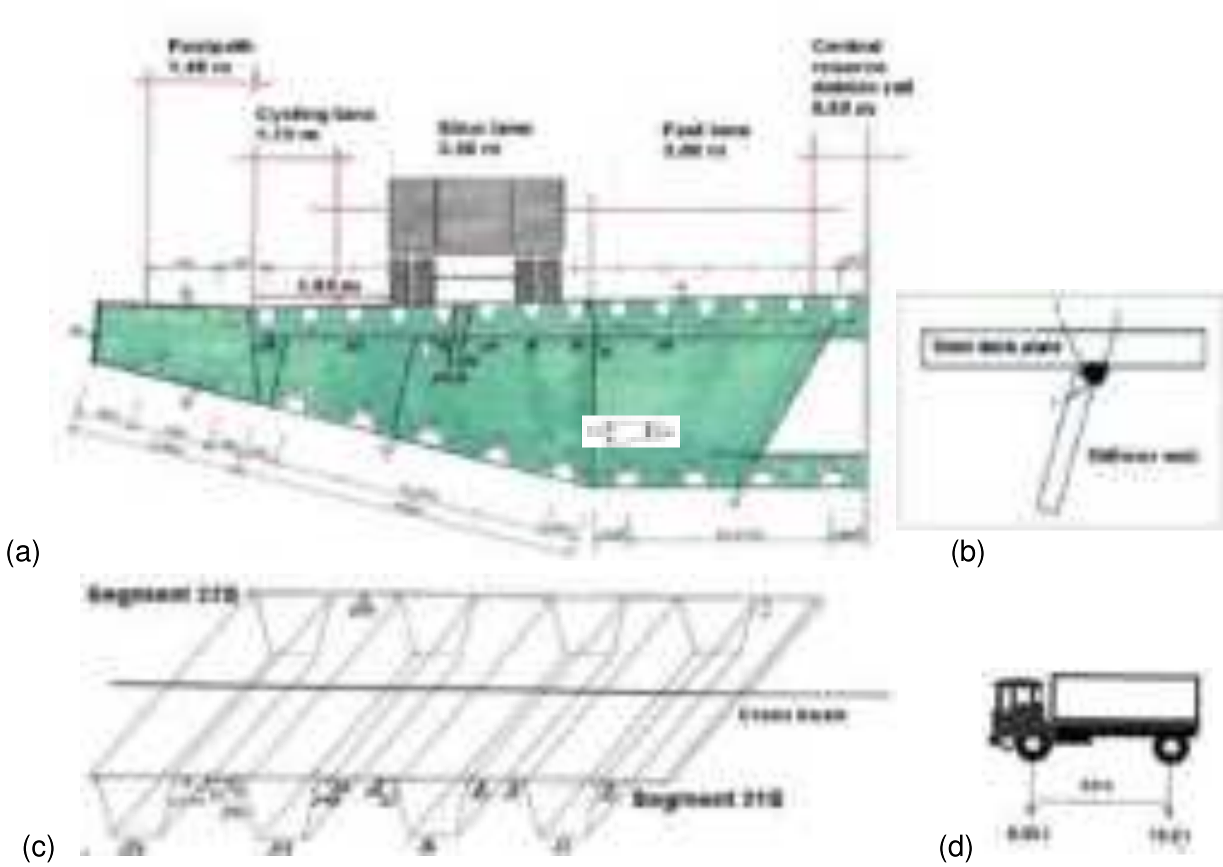


Figure 60 (a) Bridge of Normandy, transverse cross section, (b) detail sensitive to fatigue, (c) stain gauges, and (d) test truck.

The influence lines are then of short support, and vary in terms of height and width (Figure 61).

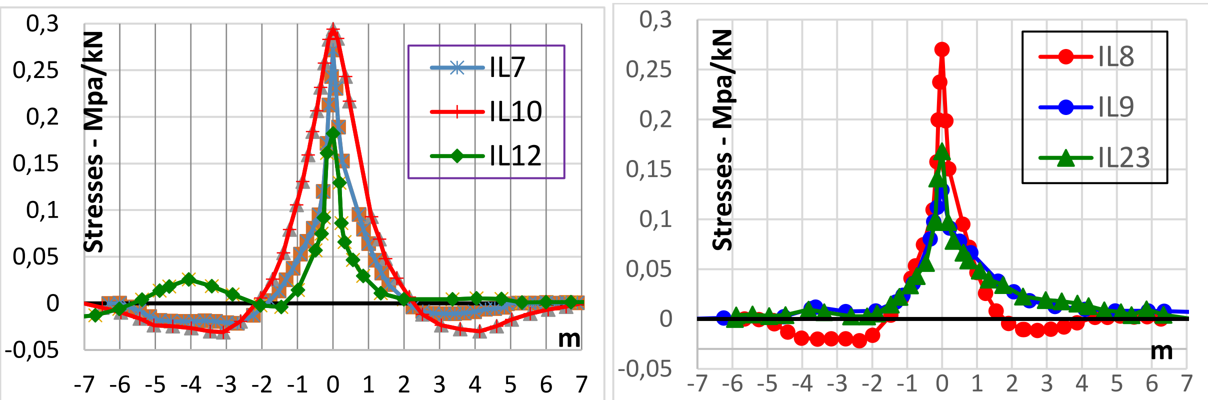


Figure 61: Influence lines: stiffener flange (left), upper plate/deck (right)

When realizing the comparison of the aggressivity of trucks and convoys of trucks for the lateral issue, we apply all trucks to the central influence line, or we create lateral variation (50%-18%-7% as for the Eurocodes or 20%-20%-20%).

The aggressivity of traffic is increased if all vehicles travel in the same lateral position (see Figure 62).

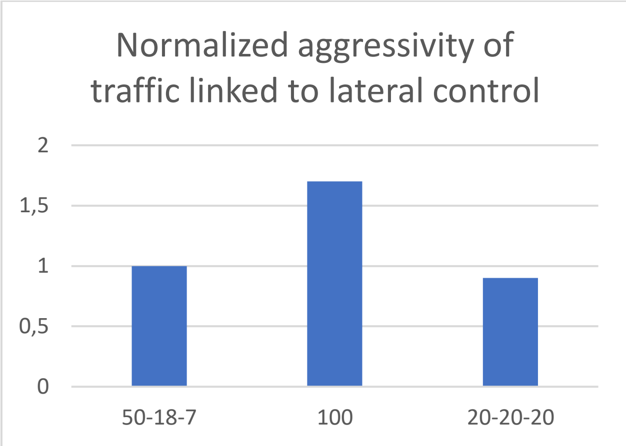


Figure 62: Aggressivity of traffic for various lateral positions of truck 1: following the Eurocodes guidelines (50-18-7), all trucks laterally controlled (100), or completely scattered (20-20-20).

4.7. Summary and Conclusion

This synthesis of the calculations done on the impact of platoons on bridges shows that:

- Bridges can be considered as specific infrastructure points in the road network, where specific, localized traffic regulations might be applied in order to control the wear/damage to the infrastructure,
- The longitudinal issue might be solved by dissolving the platoons, or by increasing the gap.
- The lateral issue can be solved by specifying some localized rules about the lateral positions of the trucks within the platoon on the road.

5. SUBTASK 4.1.3: IMPACT ON TUNNELS

5.1. Background

After assessing the impact of multi brand platooning on pavement and bridges, this task 4.1 goes on with assessing the impact on tunnels, or more precisely the opportunities and the hurdles of this type of semi-autonomous driving in tunnels.

For bridges and pavements, the work has mainly focused on the physical impact of platooning, by assessing experimentally and calculating the wear caused by platoons, compared to current traffic. This has shown that the parameters that describe the platoon (number of trucks, loading of trucks, longitudinal gap, lateral positioning in lane) are very important, and can be the opportunity for the road operator to better manage the heavy traffic. In particular, the need for the road authorities to obtain precise, real-time information on the traffic has been shown.

As far as tunnels are concerned, the methodology will be different. Indeed, the initial finding is different: as already stated previously (Franziska Schmidt, 2017), (Franziska Schmidt, 2018), the physical infrastructure itself will not be affected by this new type of freight, but safety issues might arise.

5.1.1. Absence of structural impact on the tunnel structure

The introduction of platoons does not have an impact on the structure of tunnel.

Of course, the pavement of the road within the tunnel will undergo the same impact as the (same) pavement outside the tunnel. As far as the geometry of the road within the tunnel is concerned, it is supposed to comply with the national design rules, in terms of curvature, gradient, …, so there should not be any issues of manoeuvring.

One point which might be an issue when dealing with platoons is the existence and number of emergency slots. Indeed, more vehicles within the tunnel at a given time might lead to more needs in terms of emergency parking. This could be a safety issue.

5.1.2. Safety issues

Therefore there exist safety concerns, which are more or less linked with the risk of accident within the tunnel:

- The fire risk is the main one: while overheating engines could be a reason leading to such an hazard, the real concern linked with platooning is that it could lead to more trucks within a tunnel, and therefore higher fire potential (Heger et al., 2020). This fire potential is linked to the type of load and its volume. The consequences of such an event are linked to the type of tunnel, the emergency parking and escape routes, and of course the level of fire potential.

- Another safety issue is the accidents that could occur within a tunnel: some tunnel operators consider that, as platooning leads to decreased distances between trucks, this risk would increase. On the other side, as the V2V communication should lead to faster emergency braking, other tunnel operators consider that platooning would be an advantage (Heger et al., 2020). This risk is closely linked to the communication possibilities within the tunnel.

These facts mean that dealing with the introduction of platoons should be dealt with risk analysis, making it possible to highlight the various opportunities and consequences. This risk analysis is site-specific (tunnel specific), and is under the responsibility of each tunnel manager.

Nevertheless, to answer the potential impacts of platooning on tunnels, an overview of the current status of management of tunnel needed to be made.

5.2. Methodology

The first step has been to conduct interviews with two, very different, tunnel operators:

- On one side, a private tunnel operator sees platooning as the opportunity to decrease the safety distance between trucks in his tunnel. In fact, the 1 second provisioned to take into account the delay of the driver reaction will be deleted. This will make it possible to increase the number of trucks within the tunnel (and therefore the income in terms of tolls), and decrease the waiting queue at the entrance of the tunnel. To test platooning, this entity has launched platooning tests, on his own, by implementing communication means within the tunnel.

- On the other side, we discussed the situation with a public tunnel operator: this entity has to manage many tunnels, with very low budget. This means that, in general, there are no communication means within the tunnels, in particular between the tunnel and the vehicles. Moreover, the possibility and/or the stability of the V2V communications within the tunnel cannot be ensured. Without new information or new means, this tunnel manager intends to forbid platooning within his tunnels.

The variety of situation has shown us that an overview was necessary: Are operators more inclined to react like the first one, or the second one? Are there reactions or ideas which would be intermediate between these two extremes? What incentives could be found to allow platoons in tunnels? What recommendations to make to tunnel operators to maximize the positive impact of platooning (or other autonomous driving), and optimize the traffic within the tunnel?

Therefore, this report will detail the answer to the various questions of the questionnaire, and comment them. After that, conclusions will be drawn. This report finishes with a conclusion.

The questionnaire has asked questions about the location and the geometry of the given tunnel, and the behaviour of the tunnel manger towards connected and/or automated traffic. The complete questionnaire can be found in Appendix B.

5.3. Answers to the questionnaire

5.3.1. Identification of the respondent

The first question has dealt with the identification (name, email address, country) of the person filling in the questionnaire. In this report, for privacy reasons, only the country of the person answering the questionnaire is given.

Number of answer	Country
1	France
2	Sweden
3a	Poland
3b	Poland
4	Oresund
5	Japan
6	Germany
7	Singapore
8	Portugal
9	Portugal
10	Portugal
11	Portugal

A variety of countries have answered, with European and non-European countries, and private and public tunnel operators. The panel of answers are deemed to show a good representation of the situation.

5.3.2. Tunnel name (or other road infrastructure)

The second question has dealt with the identification of the tunnel.

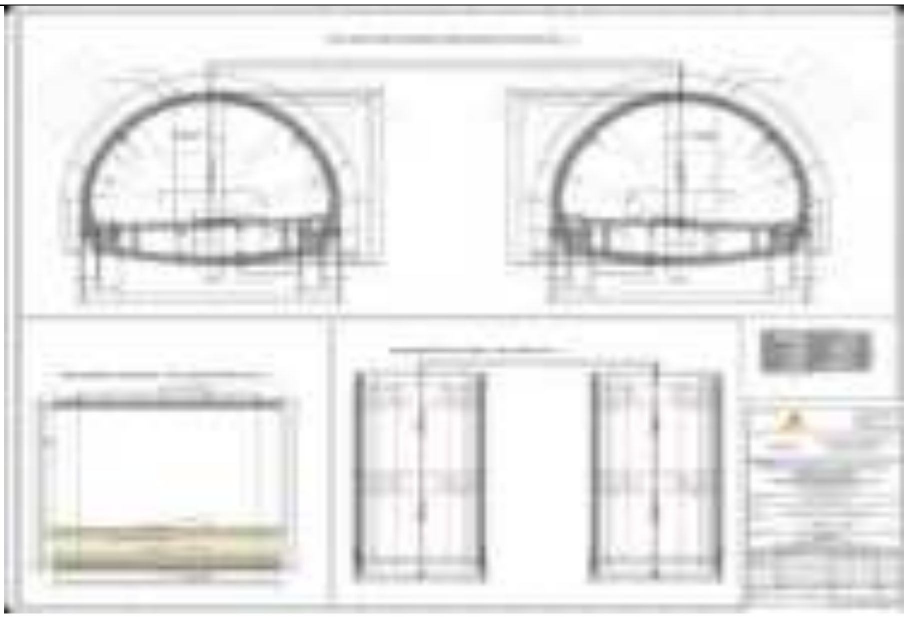
Number of answer	Tunnel name

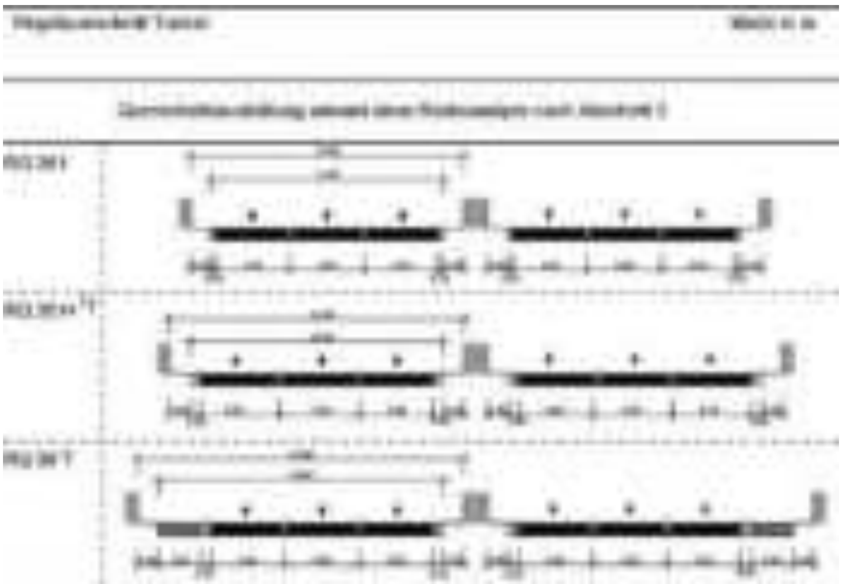
1	Tunnel du Mont-Blanc / Mont-Blanc Tunnel / EEIG-TMB
2	3 main highway tunnels in Stockholm A. The Southern Link tunnel (in operation) B. The Northern Link tunnel (in operation) C. The E4 Stockhom bypass (under construction)
3a	Mały Luboń tunnel (Construction of express highway S7 Kraków – Rabka Zdrój, section between Naprawa – Skomielna Biała from km 721+170 to 724+220)
3b	TS-14, TS-04
4	Øresundstunnelen
5	…
6	Several Tunnels on motorways and federal roads on the territory of the Free and Hanseatic City of Hamburg, Germany
7	Kallang/Paya Lebar Expressway (KPE) Marina Coastal Expressway (MCE)
8	Portela Tunnel
9	A4 – Marão tunnel
10	Castro Daire Tunnel
11	….

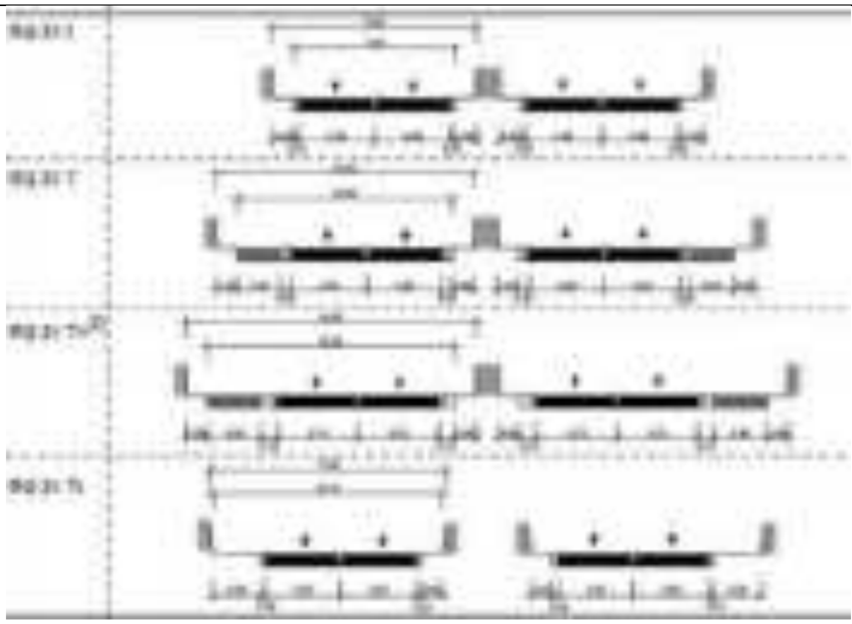
5.3.3. Geometry of tunnel

The aim of this question was to obtain information about the general geometry of the tunnel, in order to have some understanding in terms of the consequences in case of accident, and in terms of adaptation possibilities for the traffic management.

Number of answer	Geometry of tunnel
1	• Bidirectional • Length : 11,6 km • Width at basis : 8,6 m • Width of carriageway : 7 m • Altitude: 1274 m (France), and 1381 m (Italy) • Maximum altitude : 1395,5 m (at the middle of the tunnel) • 1 tube • 1 lane per direction 
2	Two separate tunnel tubes, number of lanes ranging from 2-3 in each direction. Exits every 100-150 m, consisting of fire locks with minimum three chambers. The tunnels B) and C) have installations corridors running along the whole length of the tunnel. 
3a	''Horseshoe'' tunnel section

	
3b	TS-14:Rectangular section  TS-04: Rectangular section 
4	

5	
6	Length: from appr. 200 m to 3000 m Height: from appr. 4,20 m up to 4,80 m “usable” height for traffic (excluding “safety space” to technical equipment on ceiling), mandatory in Germany: minimum 4,50 m from pavement to ceiling or equipment Width: for most tunnels 3,25 m, 3,50 m or 3,75 m per lane plus on both sides safety space to the curb of 0,25 – 0,50 m and pedestrian emergency pathways of 1 m each, some tunnels have also hard shoulders with widths from 2 m up to 3 m. Standard Cross sections in Germany as follows (excerpt from EABT 80/100). 

	 
7	KPE - twin-cell box vehicular tunnel structure MCE - twin-cell box vehicular tunnel structure
8	Tunnel with two twinned galleries 12,5m x 8,95m (L x H), 815m long, in a motorway section with a 2x2 track profile. Main galleries with 41,5m of wheelbase. It also has two connecting galleries, one for pedestrians and another for vehicles.
9	The Marão tunnel consists of two parallel tunnels, called the North Tunnel (East / West) and South Tunnel (West / East), with approximately 5 667 m each, which cross the Serra do Marão, and is part of the A4 highway between Amarante and Vila Real. The two galleries are 13,84 m apart between the left limits of the respective lanes. 

10	2 linear pipes with another pipe connecting both. Tubes are almost circular.
11	

The listed geometries are quite disparate, showing various types of tunnel construction.

The width of the lanes are compliant with the dimensions of lanes outside tunnels, so there should not be any lateral positioning issues.

5.3.4. Number of tubes, diameter, number of lanes

This question asks about the number of tubes, the diameter and the number of lanes of the tunnel.

Number of answer	Number of tubes, diameter, number of lanes of the tunnel
1	• 1 tube, • 1 lane per direction.
2	A. 2 tubes, 2-3 lanes, tunnel 10-15 m wide, B. 2 tubes, 2-3 lanes, tunnel 10-15 m wide, C. 2 tubes, 3 lanes, approx. tunnel 15-18 m wide.
3a	2 tubes, Section: 16,8m (width) - 11,45m (height), 2+1 lanes per tube. 
3b	TS-14: • Length: 496 m, • No. of lanes: 2,

	• Width: 36.6 – 39.1 m, • Height: 5.00 m. TS-04: • Length: 653 m, • No. of lanes: 2, • Width: 37 m, • Height: 5.00 m.
4	• 2 road tubes, 2 lanes in each, • 2 rail tubes, 1 track in each.
5	
6	Tubes: in general 2, one tunnel with 4 tubes, Diameter: defined with width and height (Height: from appr. 4,20 m up to 4,80 m “usable” height for traffic, Width: for most tunnels 3,25 m, 3,50 m or 3,75 m per lane plus on both sides safety space to the curb of 0,25 – 0,50 m and pedestrian emergency pathways of 1 m each). Number of lanes per tube: 2, 3 and 4 (some with additional lanes for entry and exit ramps).
7	A. KPE : 3 lanes dual carriageway, Twin-cell box with approximate 15m width. B. MCE : 5 lanes dual carriageway, Twin-cell box with approximate 48m internal width.
8	Number of tubes : 2,

	Number of lances: 2, Diameter: 12,5 m.
9	The Marão Tunnel consists of two tubes, operated unidirectionally and have a vaulted cross section. In each tube, traffic is operated on two lanes and the tubes are equipped with an additional emergency lane. Number of tubes: 2, Diameter: 12 m (maximum), Cross section type: Vaulted (75 m²) , Number of traffic lanes + emergency lanes: 2 + 1.
10	2 tubes, 10,50m per tube, 2 lanes, Height allowed 4,70m.
11	

The answers to the questionnaire show a high variation between the geometries of the tunnels: for some tunnels, there is only one tube, somewhere there are several of them (also by separating the various types of transport modes, for example pedestrians and vehicles).

Moreover, some tubes are composed of traffic lanes in opposite directions, whereas others separate the traffic in given directions (one tube per direction).

5.3.5. Road alignment, longitudinal profile

This question is related to the geometry of the road within the tunnel.

Number of answer	Road alignment, longitudinal profile
1	Curve at both entrance, straight inside.
2	It varies in all three tunnels, main tunnels usually up to 3,0-3,5 % slope, connecting ramp tunnels up to 5% slope.
3a	Tunnel length 2.057 m: 70% straight and 30% in road curve (2.800 m radius).

	Tunnel slope 0,5%. 
3b	TS-14:  Crest vertical curve R=7500 m, Longitudinal slope -3,19 % to -3,50%. TS-04:  Sag vertical curve R=2000 m, Longitudinal slope: ±4,6%.
4	
5	
6	From almost 0% up to 4% longitudinal gradient, up to 6 % at ramps. Alignment generally designed for 80km/h.
7	• KPE: Approximately 9km long tunnel,

	On and off connection slip roads. • MCE: Approximately 3.8km long tunnel, On and off connection slip roads.
8	Tunnel length 815m, with a 2.98% longitudinal slope.
9	Both sides are composed, each, by a 2.5% longitudinal slope along 5 203 m (south, w / e) and 5 208 m (north, e / w) of development, agreed through vertical curves convex rays of 16,000 m, at their ends, where the traces start and end. Maximum longitudinal slope: 2,5% Altitude above sea level (west/east portal) : 640 m / 775 m.
10	Linear road, all tube is visible for the drivers. Longitudinal profile with 2,7% of inclination.
11	…

The longitudinal geometries of the road within the tunnels are compliant with the design regulations of roads outside tunnels: the road curvatures are sufficient, and the gradients are also acceptable.

Nevertheless, two elements of these geometries could be issues for platooning trucks:

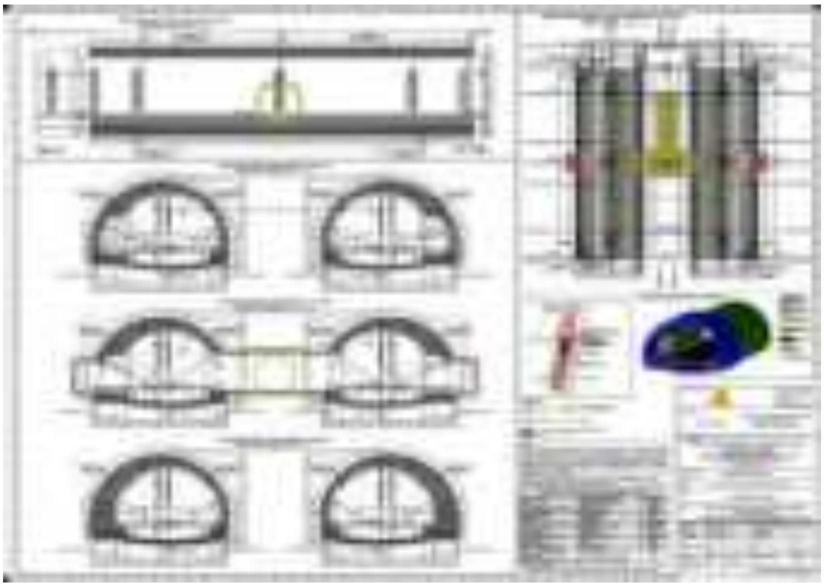
- Slopes of ±5% can be problematic as platoons may not be stable, depending of the power of the engine of the truck in front of the platoon. Therefore, communication of the gradient would be an advantage for the platoon. Even better, information of the gradient could make it possible for the platoon to be rearranged in an optimized way, making it possible to drive at the highest possible speed for all trucks within the platoon.

- Curves at the entrance and the exit of the platoon: these elements of geometry are crucial for platoons, especially in the case of a possible momentary connection loss at the entrance in a tunnel. Therefore, this is also an information which could advantageously transmitted to the platoon.

Therefore the geometry of the tunnel could be transmitted to the platoon, through I2V, for safety and optimization reasons.

5.3.6. Emergency places for trucks (and their geometry)

In previous works (Franziska Schmidt, 2017, 2018), the existence, the number and the geometry of the emergency parking has been targeted as a potential issue in case of authorization of High-Capacity Vehicles. This issue can be extended to the case of authorization of platoons within tunnels, as therefore there might not be enough emergency parking slots available for all trucks inside the tunnel at a given time.

Number of answer	Emergency possibilities
1	1 garage of 28 m, each 600 m on the right side
2	Emergency lane, 2 m-wide, provided throughout all tunnels, main tunnels and ramps.
3a	1 lay-bis dim. 2,5x55m per tube 
3b	No
4	No
5	…
6	For vehicles detected by height control to be checked by police: appr. 6 m x 40 m
7	Road shoulders
8	No
9	Both tubes have a 2.50 m wide emergency lane (continuous emergency stop).

10	No
11	Túnel de Alpedrinha (#3) : • Pk 150+800 (S/N) – 595m^2 (approx. 60m x 13m), • Pk 151+200 (S/N) – 535m^2 (approx. 48m x 10m), • Pk 151+800 (N/S) – 548m^2 (approx. 34m x 10m). Túnel da Gardunha (#2) • Pk 152+000 (S/N) – 230m^2 (approx. 35m x 8m), • Pk 153+950 (N/S) – 513m^2 (approx. 55m x 12m). Túnel da Ramela (#4) • Pk 201+600 (S/N) – 327m^2 (approx. 29m x 8m), • Pk 202+050(N/S) – 365m^2 (approx. 30m x 9m), • Pk 203+400 (N/S) – 373m^2 (approx. 30m x 9m), • Pk 203+400 (S/N) – 370m^2 (approx. 29m x 9m). Túnel do Barracão (#4) • Pk 206+400 (S/N) – 290m^2 (approx. 28m x 8m), • Pk 206+470 (N/S) – 305m^2 (approx. 30m x 8m), • Pk 207+300 (N/S) – 328m^2 (approx. 30m x 8m), • Pk 207+250 (S/N) – 352m^2 (approx. 32m x 10m).

These answers about the emergency parking/lane is already an issue nowadays, for some tunnels, for the “conventional” traffic. This point will have to be studied specifically for each tunnel, by risk analysis, and by taking mitigation measures: in particular, adapted traffic management procedures could ensure that there are enough emergency parking places.

It should be noted that dealing with this issue means also taking into account the emergency exits within the tunnel (see next section).

5.3.7. Current traffic management

During discussions with a private tunnel operator (see Section 5.2 for more information), it has been proposed –by the tunnel operator – that the longitudinal gap between the trucks within the tunnel could be decreased from 250 m to 150 m, by taking into account that the 2 seconds reaction time of the truck driver can be decreased to 1 s.

Number of answer	Current traffic management
1	• Video surveillance with automatic detection of incident, with 120 cameras, • Centralized Technical system with more than 35 000 points monitored, • Barriers inside the tunnel, • Toll gate at each entrance.
2	Generally, all traffic is allowed. Some restrictions regarding transport of dangerous goods can occur. Examples of technical installations: • Traffic Control Center 24/7/365, • PCMS (Plant Control and Monitoring System). • CCTV: cameras throughout including detection for stopped vehicles, • Various detection systems including fire, • Longitudinal fire ventilation. • Fixed fire fighting system (in tunnels B) and C)), • Emergency exits every 100-150 m: Hand held fire extinguishers plus emergency phones are located in the emergency exits. • Variable message signs,

	• MCS, • Drainage, • Full mobile phone coverage and fire fighters' radio, • Boom gates to close tunnel entries.
3a	Heavy trucks, light vehicles, and Military vehicles (STANAG) are allowed within the tunnel.
3b	TS-14 and TS-04: Variable message signs.
4	• Control Center in Sweden (the tunnel is situated at the Danish side): 24/7/365, 2 operators, one handling traffic control and technical issues, and the other handling the Toll Station. • PCMS (Plant Control and Monitoring System). • CCTV cameras in the road tunnel every 60 m, detecting stopped vehicles. • Longitudinal fire ventilation. • Emergency doors every 88 m. • Emergency stations every 88 m.
5	…
6	Lane signaling, dynamic traffic signs, stop signs, variable message signs, height control, ban on overtaking for trucks, some tunnels with ban on hazardous goods transport, requirement for trucks in general to keep on the rightmost lane.
7	Maximum allowable vehicle type – Maximum allowable HGV dimension, 13 m length and 3 m width and 4.5 m height.
8	Average annual daily traffic per section: 2343 (E-W),2489 (W-E). Heavy Vehicles Percentage: 4 %, Maximum peak of vehicles: 3250 per day (August).

9	Tunnel Scada-TMS with electronic signage, CCTV monitoring, Event Detection Systems, Dangerous Goods Detection.
10	Trucks and light vehicles allowed.
11	A SCADA for traffic management (traffic counters and VMS)

The answers to this question show that there exist many traffic control measures with the tunnel, which leads to specific traffic management procedures.

It should be noted here again that safety could be increased by communication between the tunnel and the vehicles:

- I2V: Currently traffic management is broadcasted by variable message signs. This could be also done, at the same time, through I2V communication.
- V2I: Currently, stopped vehicles and dangerous goods are detected with dedicated sensors. This information could be confirmed by direction communication from the trucks. This would mean an emergency signal if the truck has stopped, and a message indicating the type of loading (categories to be defined based on the fire potential).

5.3.8. Adaptation of traffic management

This question is about the possible adaptation of traffic management procedures, if autonomous traffic is allowed within the tunnel. This questions deals with autonomous mobility, the non-autonomous one and the mixed one.

Number of answer	Adaptation of traffic management
1	To be defined. Thinking about closing the circulation on the opposite side.
2	Currently not planned for autonomous traffic. However, there is space available in the technical rooms, so if new technology becomes the new standard there should be opportunities to install new technology.
3a	None
3b	None
4	No autonomous traffic
5	Not specifically implemented in Japan.

6	If all traffic in a tunnel is autonomous with fully established I2V and V2I, I would expect less traffic management equipment in and outside the tunnels.
7	• Need to consider the incident management plans to manage incident involving autonomous vehicle in road tunnel and communications channel for prompt recovery. • Need to consider the possibility of autonomous vehicles technology to trigger alerts when involved in incident in road tunnels.
8	None
9	The TMS and Scada systems got to be connected to the C-ITS system to ensure that all the systems and information are merged.
10	…
11	At the moment we have no plans for adaptations of the traffic management system.

This answer shows the various possibilities of reaction from the side of the road operators:

- Some tunnel operators might not change their traffic management procedures if autonomous traffic is allowed. This behaviour might change after some time, when opportunities and (new) safety issues arise. Nevertheless, if this change of behaviour comes too late, it might be difficult to change the rules of driving and accessing to the tunnel for autonomous traffic (for example, implement new communication strategies).

- Other tunnel operators, in particular those involved in C-ITS research projects, are combining data coming from the vehicles and data measured by the infrastructure to open whole new possibilities. This is R&D work, which can be lengthy and expensive, which explains why it is a good solution to tackle that within a (partially) public-funded research project. This new approach could lead to better safety procedures and new opportunities (new business possibilities?).

To finish, it should be noted that, during our discussions (see Section 5.2), one tunnel operator has mentioned that he intends to forbid autonomous traffic within his tunnels as the danger is not well understood currently, for these tunnels (no extensive ITS and sensor possibilities, no high budget availabilities). This would mean that the platoon would have to dissolve before entering the tunnel.

5.3.9. I2V

This question deals with the existence of I2V within the tunnel. If the answer is yes, what I2V technology is used, and what are the sent messages (format, content)?

Number of answer	I2V
1	• sign panels, • FM radio.
2	• Information via FM-band, various public and commercial channels. • DAB is evolving: Small incident, no reason to evacuate, Medium incident, no reason to evacuate, Major incident with fire and/or DG, evacuate the whole tunnel. • Variable message signs able to communicate evacuation messages: As new technology develops these variable message signs will have new functions. Tunnel C) has fully graphical signs so we can use pictograms for both fire and traffic conditions (queue, accident, other hazard). • Traffic control centre regularly publishes traffic information in various channels, including radio, internet etc.
3a	None
3b	None
4	• Information via FM-band, different Danish and Swedish channels. Small incident, no reason to evacuate Medium incident, no reason to evacuate Major incident with fire and/or DG, evacuate
5	…
6	I2V present: radio broadcast channels (messages from PA system in case of incident are being transmitted also into radio broadcast channels), Technology: not in my expertise to assess,

	Content of Messages: warnings and instructions in case of incidents, emergency stop at tunnel portal.
7	The current approach for communication with motorists is via radio break in broadcast capabilities, Variable message boards and lane use signs.
8	None
9	None. We are in C-Roads an 5G-Mobix projects trying to evaluate the best solution for this issue.
10	None
11	We are participating in the C-Roads Portugal project with a pilot in the Gardunha Tunel for the implementation of C-ITS services, with 5G technology.

The answers to the questionnaire show 3 groups of tunnel operators concerning this existence of I2V communication:

- Those who have installed no communication means within the tunnel,
- Those who have installed V2I communication means, and who are generally part of ITS R&D projects,
- Those who have “traditional” communication means, like variable message signs or broadcasting on radio channels.

This differences in behaviours may be linked to differences in opportunities and/or budget.

5.3.10. V2I

This question deals with the existence of V2I within the tunnel. If the answer is yes, what V2I technology is used, and what are the sent messages (format, content)?

Number of answer	V2I
1	None
2	None
3a	None

3b	None
4	None
5	None
6	V2I: not existent Possible content: incidents, hazardous goods vehicles
7	In development progress. Should advocate autonomous vehicle to auto trigger alerts when involved in traffic incident.
8	None
9	None. We are in C-Roads an 5G-Mobix projects trying to evaluate the best solution for this issue.
10	None
11	We are participating in the C-Roads project with a pilot in the Gardunha Tunel for the implementation of C-ITS services, with 5G technology.

The conclusion is the same as above, on I2V communication.

5.3.11. Communication means in tunnel

Number of answer	Communication means in tunnel (what are the communication means in the tunnel, already installed or intended? WIFI, 5G, …)
1	• Radio, • test with 5G will be done during 2020.
2	• Tetra communication system for the Emergency Authorities, • Communication system for FM-broadcasting traffic-messages, • Communication system for commercial mobile facilities: No WIFI, • Emergency phones located in emergency exits and tunnel portals,

	• Phones in technical rooms for service personal.
3a	5G communication has been planned.
3b	TS-14 and TS-04: Radio communication network.
4	• Tetra communication system for the Emergency Authorities, • Communication system for Danish train-radio (STR), • Communication system for Swedish train-radio (GSM-R), • Communication system for FM-broadcasting traffic-messages, • Communication system for commercial mobile facilities (KMT, Cell-phone 3G, 4G etc.) , • 99 emergency phones in Motorway and Railway tunnels, • 121 service phones in technical rooms.
5	…
6	Already installed: Radio broadcast, digital radio network for emergency and maintenance services, mobile radio communication (in parts 5G).
7	1) Communications System for motorist, such as: a. FM Radio Re-Broadcast & Break-In System (RBBI), main purpose is to broadcast emergency messages to motorist in their vehicle via their FM radio for emergency broadcast and for instructions; b. Tunnel Public Address System to provide audible announcements to motorist travelling along the tunnel carriageways and also in the emergency escape staircases; c. Help phones in emergency escape staircases to allow motorist to communicate with the Operation Control Centre for assistance in time of need; d. Emergency Telephone System (or SOS phones) which are located along tunnel walls at every 100m interval to provide a means for motorist to communicate with the Operation Control Centre for assistance.

	2) Communications System for emergency and maintenance personnel, such as: a. Operation & Maintenance Radio System (2-way voice communication radio), to provide maintenance personnel a means to communicate with the Operation Control Centre and with their maintenance team. b. Emergency Response Team / Police Radio System (2-way voice communication radio), to provide the Authorities a means to communicate with their Operation Control Centre. 3) Communications System provided by commercial facility providers such as the mobile service providers: a. 3G/4G mobile voice and data communications; b. 5G technology is currently being considered and plans are underway to implement them in the KPE/MCE tunnels.
8	4G (Vodafone + NOS)
9	In C-Roads we are testing G5 solution and in this project, we have tunnel coverage, but we have not testing the Platooning Use Case. In the future we intent to test both technologies.
10	GSM, SIRESP – Digital communication system to Emergency and Police Services.
11	Communication means in the tunnel, already installed: GSM and Tetra communications, Communication means in the tunnel, intend: 5G.

The answers to this question shows that several tunnel operators have begun (or intend to) install cellular communication means. These are of various types: 5G, G5 and 4G are being listed.

It should be noted that WIFI/WLAN is not cited here.

This should make it possible for the trucks of the ENSEMBLE platoon to communicate within these tunnels, and communication loss could be avoided within the tunnel. Some points remain open or to be tested, as for example the probabilities of connection loss at the entrance/exit of the tunnel, the possible billing procedures, …

5.3.12. Tunnel Structural Health Monitoring (SHM) or other monitoring

This question is about the existence of structural health monitoring of the tunnel. While the direct link between traffic and infrastructure wear is not direct for tunnels, a link between both sorts of databases could be beneficial, for example in case alerts are given from side of the SHM. It could also make it possible to predict some values (for example, CO and NO values according to traffic composition).

Number of answer	Tunnel SHM or other monitoring
1	GTC named LOGOS
2	..
3a	Manual geo-structural monitoring of the final lining.
3b	TS-14 and TS-04: • Measurement of the CO and the NO, • fire detection system, • alarm point system, • video surveillance system, • motion control system.
4	No kind of health monitoring. We are in progress of introducing AI (starting in the very small).
5	…
6	Laser beam to detect movements of the tunnel structure (monitoring potential salt stock settlement).
7	Automatic Incident Detection (AID) and CCTV surveillance system
8	Only Scheduled Visual Inspections.
9	Our sensor systems along the tunnel are connected to a SCADA system for real time monitoring and operation.

10	Topography on ventilators body to anticipate any movement of them.
11	The tunnel structural health monitoring is made manually and periodically.

Here again, there exist a big variety of situations concerning monitoring within the structure: while some tunnels monitor the structure itself (movements of the structure itself), other monitor the environment within the tunnel (movements of the ventilators, CO and NO levels, …), while others do no measurements.

This might once again be linked to the budget availabilities.

5.3.13. Issues linked to cross-border issues: different regulations, roaming, …

Tunnels may connect two countries, and therefore the rules and procedures of managing the tunnel and/or the traffic within the tunnel must be acceptable on both sides. Therefore, it has been asked which issues are foreseen.

The answers listed:

- Different languages,
- Different cultures,
- Different regulations: this is getting better with common EU regulations but they are sometimes still implemented differently,
- Separated Emergency Communication systems, this can be solved with a gateway-system,
- More radio channels, more cell phone communication providers, etc.

5.3.14. Comments (for example, other encountered issues)

Some thoughts on platoons in tunnels:

- The limited space between platooning vehicles might be a problem in case of a fire in a tunnel regarding the hazard of fire spreading from one vehicle to the adjacent vehicle. One want as much space as possible between vehicles in case of a fire in a tunnel to prevent spreading.
- In case of an incident (fire, accident, …), it is very important for emergency services to have good access into the tunnel. In these situations tunnels are often full with stopped vehicles which cannot leave the tunnel because the way out is blocked by the incident or because of other reasons (e.g. congestion). Emergency services will need space to get to the location of the incident, therefore tunnel users are requested to form an emergency corridor in the

tunnel. To clear the path for emergency vehicles the other vehicles have to manoeuvre towards the tunnel walls / the hard shoulder. This process of manoeuvring is far more difficult if the vehicles have limited distance between each other. This should be taken into account. This problem might also occur outside tunnels in case of congested roads / motorways.

- In highly trafficked tunnels, we often experience a lane full of trucks not complying with mandatory distance between the trucks. This leads to a kind of "wall" of trucks on one side of the tunnel (trucks have to use the rightmost lane in tunnels in general). Not only for the above mentioned aspects (fire spreading, manoeuvring for emergency corridor) this is not desirable, it has also effects on the visibility of safety elements in tunnels (emergency exit doors, emergency telephones etc.) and leaves limited space for tunnel users evacuating.

- Other issues are: How to deal with breakdowns within the platoon? How to get the broken-down vehicle / the whole platoon out of the tunnel (thinking of space for towing vehicles, required time to remedy and availability of tunnel infrastructure)?

- Automatic video detection systems in tunnels tend to give false alarms or false counts of the number of vehicles when the distance between trucks is too small (depending on the location of the video cameras).

Platooning in tunnels is not just limited to the technical solutions, but also very dependent on fire safety strategies and the general traffic conditions regarding on- and off-ramps. From a fire safety perspective, it is not preferred to have for example three big trucks driving very close to each other. Also "normal" traffic has to be able to enter and leave the tunnel if on- and off-ramps are present.

5.4. Synthesis and recommendations

5.4.1. Expected impacts of platooning

The driving of platoons, compared with the current heavy traffic, may have the following impacts on the tunnel:

- Higher fire potential: when authorizing more trucks in the tunnels, the fire potential of the whole carried load within the tunnel may be higher. Two facts can mitigate this consequence:
    - On one side, it is needed to compare this platooning state with the current traffic within the tunnel: if trucks comply with the regulations (minimum of 2 s gap between the trucks), platooning increases the number of trucks in the tunnel on a given time, and therefore the fire potential. Nevertheless, on some roads/tunnels trucks do not comply with the mandatory distances between trucks, therefore platooning could be a way to monitor and regulate the distance between trucks. This point can be found also in the work on the impact of tucks on pavements and bridges.

  - On the other side, tunnel operators could use the V2I communication to obtain a better information on the type of carried load. Using this information makes it possible to reassess the fire potential along time, and if necessary to stop some trucks at the entrance of the tunnel until the fire potential has reached an acceptable level. This would also mean V2I communication, with real-time information about the load, sent before the entrance in the tunnel.

- Accident risk: the assessment of this risk with platooning depends on the authors:

  - Some authors consider this risk as decreased with platooning (Heger et al., 2020) as communication between trucks will make it possible to avoid many accidents, and in particular those where there is an emergency braking of the truck in front.

  - Other authors consider that platooning will increase the accident risk as the trucks will drive closer to each other.

    It is generally accepted that platooning will increase safety as it will decrease the number of accidents (Rahman & Abdel-Aty, 2018), so that the accident risk is decreased if the correct functioning of the platoon function is ensured.

5.4.2. Synthesis of actual status of autonomous driving in tunnels

Some R&D projects are currently testing and demonstrating platooning (or platoon-like driving) within tunnels. As example, one can cite the current testing at Tunnel du Mont Blanc and project KoMoD in Düsseldorf (Böhnke PL, 2020). Some feedback can be made:

- V2I enables early detection, in particular of overheated engine,

- I2V may give information about the tunnel itself, and the traffic at the given time, thus helping vehicles to deal with the changing road and/or visibility conditions, and the loss or limitation of onboard sensors.

Both communication means can be combined for both vehicle and infrastructures related purposes. While doing this, the communication should also be designed for mixed traffic, meaning "traditional" vehicles mixed with autonomous vehicles.

Some facts can also be stated; in particular the technology is available, as for example:

- The sensors, both vehicle or infrastructure based (induction loops, cameras),

- The ego information: position, vehicle status, which can be communicated with various types of data formats (DENM or CAM),

- The observer information (information on the environment) provided by the sensors of the vehicle,
- Communication means: Road Side Units, WLAN (or similar to WLAN) communications (sometimes with dedicated R1D partners, as partner SWARCO in KoMoD project (Böhnke PL, 2020)) or cellular communications (Vodafone is cited in the answers to the questionnaire.)
- Some tunnel operator have implemented a consolidated database of all this information.

5.5. Recommendations

The recommendations are the same as for pavements and bridges: if there is the possibility to combine physical and digital infrastructure (International Transport Forum, 2018) and take advantage of the opportunities brought by platooning, allowing platoons in tunnels might have benefits.

Nevertheless, there should be a common ground between tunnel operators: indeed, creating one Intelligent Access Program (or a small number of them) requires the policy makers to align. Moreover, for platooning as for other IAPs, a common platform is needed (Sjögren, 2019).

For better compliance or adhesion to this new type of mobility, the benefits should be shown: this is valid for both carriers/shippers/Platoon Service Providers who might be obliged to share data about their trucks in order to pass tunnels, but also for tunnel operators who might need to invest in sensor techniques or communication means. The return on investment needs to be investigated, for the tunnel operator (or even road operators), and the transport companies. This can best be done by case studies, for example in the frame of R&D projects. Some work has been done about this point within deliverable D4.3 "Analysis of market needs, business models and life-cycle environmental impacts of multi-brand platooning".

The facts are there: The technology exist, and (most of) the stakeholders are ready (which means that the transportation companies can adopt. The hurdles that remain are political hurdles: there are some decisions to be taken about privacy protection or about the regulation concerning platooning.

5.6. Summary and Conclusion

This part of deliverable D4.1 “Impact of platoons on road infrastructure”, deals with the impact of platoon driving on tunnels. For that, a questionnaire has been issued, and several tunnel operators have answered it.

This has shown that platooning would lead to higher or decreased safety, depending on the current traffic situation within the tunnel and the equipment (communication with vehicles) installed within the tunnel. Moreover, the behaviour of tunnel operators towards platooning is disparate, as are the sensor and communication possibilities within the tunnels.

After a synthesis and comments of the answers, recommendations have been proposed within this report: the introduction of Intelligent Access Programs, with the required telematics, could be put in place by showing the benefits for all stakeholders.

6. SUMMARY AND CONCLUSION

6.1. Subtask 4.1.1. Impact of platoons on pavements

This subsection contains a compilation of the results obtained from the research plan defined for Subtask 4.1.1. Impact of platoons on pavements. The results described in this report have been already published in peer-reviewed journals and the proceedings of international conferences. According to the results obtained, the following conclusions can be drawn:

For the experimental program:

- The construction process associated with the instrumentation of the test section at IDIADA test track facilities was successful, and there was no loss of sensors. The reproducibility and repeatability tests of the data collected with this instrumentation allowed to obtain a good quality database, which was then been used to analyse the effect of truck platoon configurations over the pavement structure tested in the project.

- The laser system used in the experiment allowed to verify the possibility to simulate platoon formations using human-driven 5-axle semitrailer trucks. The data obtained with the lasers was consistent with the results obtained from the instrumentation placed on site.

- For the type of trucks used, 5-axle semitrailer trucks with single steer and trailer tridem axles and single driven axle with two tires on each side, the transverse strains are higher than the longitudinal ones in both individual truck and platoon configurations. The values are higher for the second and third truck in the platoon configuration analysed. A strain accumulation effect is observed for the transversal strains, under the loading of closely spaced trucks, especially at high temperatures.

- The fatigue damage produced by trucks in platoon formation was determined using an original multi-axle fatigue equation based on the characterisation of the strain signals obtained from instrumentation. The data analysis determined that trucks in platoon formation can increase fatigue damage of pavements when they circulate at high temperatures, and with reduced lateral wandering patterns. These effects can be reduced by adapting parameters like lateral wander, or truck loads, and also by avoiding high temperature periods.

For the numerical modelling:

- Increased wandering patterns seem to be a good option to mitigate the damage produced by platoons in pavements.

- The developed viscoelastic model predicts well the strains produced in pavements subjected to truck platoon configurations. The model can be proposed as a tool to perform parametric studies to help optimise truck platoon configurations, so that they are more pavement friendly.
- Parametric studies based on the viscoelastic model obtained reveals that platooning trucks at low temperatures do not affect pavement structures. On the contrary, platooning trucks at high temperatures increase mainly the transverse strains. In this context, to make possible using platoons at high temperatures it is possible to play with parameters in the platoon as is the case of: (1) increasing the lateral deviation of the trucks (wandering), (2) increase the inter-truck time gaps/distances, (3) reduce the number of trucks in the platoon and (4) reducing the distribution of load in the truck.

In general, for Subtask 4.1.1.:

- The tests and associated numerical simulations have shown that platoon configuration can be adapted to keep approximately the same pavement fatigue life. The parameters related to this possible adaptation are: (1) the level of truck loading, this means the distribution of the axle loads, (2) the lateral deviation (wandering) of each truck in the platoon or between platoons, (3) the number of trucks in platoon configuration, (4) the inter-truck time-gaps/distances, (5) the traffic distribution along the year and along the time of the day, avoiding the traffic at higher temperatures, (6) the percentage of platoon penetration in the daily and annual traffic.
- Further research will continue to:
  - Improve the current multi-axle fatigue model to include characteristic parameters of platooning trucks: variable rest periods and strain accumulation, considering also the effect of different pavement temperatures.
  - Analyse the effect of varying the characteristic parameters of platoons, in additional case studies which can represent the rest of the pavement structures present in Europe and which should be used for the transport of loads using platoons.

6.2. Subtask 4.1.2. Impact of platoons on bridges

The calculations done on the impact of platoons on bridges shows that:

- Bridges can be considered as specific infrastructure points in the road network, where specific, localized traffic regulations might be applied in order to control the wear/damage to the infrastructure.
- The longitudinal issue might be solved by dissolving the platoons, or by increasing the gap.

- The lateral issue can be solved by specifying some localized rules about the lateral positions of the trucks within the platoon on the road.

6.3. Subtask 4.1.3. Impact of platoons on tunnels

The work done on the impact of platoons on tunnels has shown that platooning would lead to higher or decreased safety, depending on the current traffic situation within the tunnel and the equipment (communication with vehicles) installed within the tunnel. Moreover, the behaviour of tunnel operators towards platooning is disparate, as are the sensor and communication possibilities within the tunnels.

The recommendations are the same as for pavements and bridges: if there is the possibility to combine physical and digital infrastructure (International Transport Forum, 2018) and take advantage of the opportunities brought by platooning, allowing platoons in tunnels might have benefits.

Nevertheless, there should be a common ground between tunnel operators: indeed, creating one Intelligent Access Program (or a small number of them) requires the policy makers to align. Moreover, for platooning as for other IAPs, a common platform is needed (Sjögren, 2019).

For better compliance or adhesion to this new type of mobility, the benefits should be shown: this is valid for both carriers/shippers/Platoon Service Providers who might be obliged to share data about their trucks in order to pass tunnels, but also for tunnel operators who might need to invest in sensor techniques or communication means. The return on investment needs to be investigated, for the tunnel operator (or even road operators), and the transport companies. This can best be done by case studies, for example in the frame of R&D projects. Some work has been done about this point within deliverable D4.3 “Analysis of market needs, business models and life-cycle environmental impacts of multi-brand platooning”.

The facts are there: The technology exist, and (most of) the stakeholders are ready (which means that the transportation companies can adopt. The hurdles that remain are political hurdles: there are some decisions to be taken about privacy protection or about the regulation concerning platooning.

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8. APPENDIX A: GLOSSARY

8.1. Definitions

Term	Definition
Convoy	A truck platoon may be defined as trucks that travel together in convoy formation at a fixed gap distance typically less than 1 second apart up to 0.3 seconds. The vehicles closely follow each other using wireless vehicle-to-vehicle (V2V) communication and advanced driver assistance systems
Cut-in	A lane change manoeuvre performed by vehicles from the adjacent lane to the ego vehicle's lane, at a distance close enough (i.e., shorter than desired inter vehicle distance) relative to the ego vehicle.
Cut-out	A lane change manoeuvre performed by vehicles from the ego lane to the adjacent lane.
Cut-through	A lane change manoeuvre performed by vehicles from the adjacent lane (e.g. left lane) to ego vehicle's lane, followed by a lane change manoeuvre to the other adjacent lane (e.g. right lane).
Ego Vehicle	The vehicle from which the perspective is considered.
Emergency brake	Brake action with an acceleration of <-4 m/s2
Event	An event marks the time instant at which a transition of a state occurs, such that before and after an event, the system is in a different mode.
Following truck	Each truck that is following behind a member of the platoon, being every truck except the leading and the trailing truck, when the system is in platoon mode.
Leading truck	The first truck of a truck platoon
Legal Safe Gap	Minimum allowed elapsed time/distance to be maintained by a standalone truck while driving according to Member States regulation (it could be 2 seconds, 50 meters or not present)
Manoeuvre ("activity")	A particular (dynamic) behaviour which a system can perform (from a driver or other road user perspective) and that is different from standing still, is being considered a manoeuvre.
ODD (operational	The ODD should describe the specific conditions under which a given automation function is intended to function. The ODD is the definition of where (such as what roadway types and speeds) and when (under what conditions,

Term	Definition
design domain)	such as day/night, weather limits, etc.) an automation function is designed to operate.
Operational layer	The operational layer involves the vehicle actuator control (e.g. accelerating/braking, steering), the execution of the aforementioned manoeuvres, and the control of the individual vehicles in the platoon to automatically perform the platooning task. Here, the main control task is to regulate the inter-vehicle distance or velocity and, depending on the Platooning Level, the lateral position relative to the lane or to the preceding vehicle. Key performance requirements for this layer are vehicle following behaviour and (longitudinal and lateral) string stability of the platoon, where the latter is a necessary requirement to achieve a stable traffic flow and to achieve scalability with respect to platoon length, and the short-range wireless inter-vehicle communication is the key enabling technology.
Platoon	A group of two or more automated cooperative vehicles in line, maintaining a close distance, typically such a distance to reduce fuel consumption by air drag, to increase traffic safety by use of additional ADAS-technology, and to improve traffic throughput because vehicles are driving closer together and take up less space on the road.
Platoon Automation Levels	In analogy with the SAE automation levels subsequent platoon automation levels will incorporate an increasing set of automation functionalities, up to and including full vehicle automation in a multi-brand platoon in real traffic for the highest Platooning Automation Level. The definition of "platooning levels of automation" will comprise elements like e.g. the minimum time gap between the vehicles, whether there is lateral automation available, driving speed range, operational areas like motorways, etc. Three different levels are anticipated; called A, B and C.
Platoon candidate	A truck who intends to engage the platoon either from the front or the back of the platoon.
Platoon cohesion	Platoon cohesion refers to how well the members of the platoon remain within steady state conditions in various scenario conditions (e.g. slopes, speed changes).
Platoon disengaging	The ego-vehicle decides to disengage from the platoon itself or is requested by another member of the platoon to do so. When conditions are met the ego-vehicle starts to increase the gap between the trucks to a safe non-platooning gap. The disengaging is completed when the gap is large enough (e.g. time gap of 1.5 seconds, which is depends on the operational safety based on vehicle dynamics and human reaction times is given). A.k.a. leave platoon

Term	Definition
Platoon dissolve	All trucks are disengaging the platoon at the same time. A.k.a. decoupling, a.k.a. disassemble.
Platoon engaging	Using wireless communication (V2V), the Platoon Candidate sends an engaging request. When conditions are met the system starts to decrease the time gap between the trucks to the platooning time gap. A.k.a. join platoon
Platoon formation	Platoon formation is the process before platoon engaging in which it is determined if and in what format (e.g. composition) trucks can/should become part of a new / existing platoon. Platoon formation can be done on the fly, scheduled or a mixture of both. Platoon candidates may receive instructions during platoon formation (e.g. to adapt their velocity, to park at a certain location) to allow the start of the engaging procedure of the platoon.
Platoon split	The platoon is split in 2 new platoons who themselves continue as standalone entities.
Requirements	Description of system properties. Details of how the requirements shall be implemented at system level
Scenario	A scenario is a quantitative description of the ego vehicle, its activities and/or goals, its static environment, and its dynamic environment. From the perspective of the ego vehicle, a scenario contains all relevant events. Scenario is a combination of a manoeuvre (“activity”), ODD and events
Service layer	The service layer represents the platform on which logistical operations and new initiatives can operate.
Specifications	A group of two or more vehicles driving together in the same direction, not necessarily at short inter-vehicle distances and not necessarily using advanced driver assistance systems
Steady state	In systems theory, a system or a process is in a steady state if the variables (called state variables) which define the behaviour of the system or the process are unchanging in time. In the context of platooning this means that the relative velocity and gap between trucks is unchanging within tolerances from the system parameters.
Strategic layer	The strategic layer is responsible for the high-level decision-making regarding the scheduling of platoons based on vehicle compatibility and Platooning Level, optimisation with respect to fuel consumption, travel times, destination, and impact on highway traffic flow and infrastructure, employing cooperative ITS cloud-based solutions. In addition, the routing of vehicles to allow for platoon forming is included in this layer. The strategic layer is implemented in a

Term	Definition
	centralised fashion in so-called traffic control centres. Long-range wireless communication by existing cellular technology is used between a traffic control centre and vehicles/platoons and their drivers.
Tactical layer	The tactical layer coordinates the actual platoon forming (both from the tail of the platoon and through merging in the platoon) and platoon dissolution. In addition, this layer ensures platoon cohesion on hilly roads, and sets the desired platoon velocity, inter-vehicle distances (e.g. to prevent damaging bridges) and lateral offsets to mitigate road wear. This is implemented through the execution of an interaction protocol using the short-range wireless inter-vehicle communication (i.e. V2X). In fact, the interaction protocol is implemented by message sequences, initiating the manoeuvres that are necessary to form a platoon, to merge into it, or to dissolve it, also taking into account scheduling requirements due to vehicle compatibility.
Target Time Gap	Elapsed time to cover the inter vehicle distance by a truck indicated in seconds, agreed by all the Platoon members; it represents the minimum distance in seconds allowed inside the Platoon.
Time gap	Elapsed time to cover the inter vehicle distance by a truck indicated in seconds.
Trailing truck	The last truck of a truck platoon
Truck Platoon	Description of system properties. Details of how the requirements shall be implemented at system level
Use case	Use-cases describe how a system shall respond under various conditions to interactions from the user of the system or surroundings, e.g. other traffic participants or road conditions. The user is called actor on the system, and is often but not always a human being. In addition, the use-case describes the response of the system towards other traffic participants or environmental conditions. The use-cases are described as a sequence of actions, and the system shall behave according to the specified use-cases. The use-case often represents a desired behaviour or outcome. In the ensemble context a use case is an extension of scenario which add more information regarding specific internal system interactions, specific interactions with the actors (e.g. driver, I2V) and will add different flows (normal & alternative e.g. successful and failed in relation to activation of the system / system elements).

8.2. Acronyms and abbreviations

Acronym / Abbreviation	Meaning
ACC	Adaptive Cruise Control
ADAS	Advanced driver assistance system
AEB	Autonomous Emergency Braking (System, AEBS)
ASIL	Automotive Safety Integrity Level
ASN.1	Abstract Syntax Notation One
BTP	Basic Transport Protocol
C-ACC	Cooperative Adaptive Cruise Control
C-ITS	Cooperative ITS
CA	Cooperative Awareness
CAD	Connected Automated Driving
CAM	Cooperative Awareness Message
CCH	Control Channel
DEN	Decentralized Environmental Notification
DENM	Decentralized Environmental Notification Message
DITL	Driver-In-the-Loop
DOOTL	Driver-Out-Of-the Loop
DSRC	Dedicated Short-Range Communications
ETSI	European Telecommunications Standards Institute
EU	European Union
FCW	Forward Collision Warning
FLC	Forward Looking Camera
FSC	Functional Safety Concept
GN	GeoNetworking
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUI	Graphical User Interface

Acronym / Abbreviation	Meaning
HARA	Hazard Analysis and Risk Assessment
HIL	Hardware-in-the-Loop
HMI	Human Machine Interface
HW	Hardware
I/O	Input/Output
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
ITL	In-The_Loop
ITS	Intelligent Transport System
IVI	Infrastructure to Vehicle Information message
LDWS	Lane Departure Warning System
LKA	Lane Keeping Assist
LCA	Lane Centring Assist
LRR	Long Range Radar
LSG	Legal Safe Gap
MAP	MapData message
MIO	Most Important Object
MRR	Mid Range Radar
OS	Operating system
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
OOTL	Out-Of The-Loop
PAEB	Platooning Autonomous Emergency Braking
PMC	Platooning Mode Control
QM	Quality Management
RSU	Road Side Unit
SA	Situation Awareness

Acronym / Abbreviation	Meaning
SAE	SAE International, formerly the Society of Automotive Engineers
SCH	Service Channel
SDO	Standard Developing Organisations
SIL	Software-in-the-Loop
SPAT	Signal Phase and Timing message
SRR	Short Range Radar
SW	Software
TC	Technical Committee
TOR	Take-Over Request
TOT	Take-Over Time
TTG	Target Time Gap
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to any (where x equals either vehicle or infrastructure)
VDA	Verband der Automobilindustrie (German Association of the Automotive Industry)
WIFI	Wireless Fidelity
WLAN	Wireless Local Area Network
WP	Work Package

9. APPENDIX B. QUESTIONNAIRE

In this appendix, the questionnaire that has been sent out by the PIARC committee for tunnels is reproduced.


ENSEMBLE

EUROPEAN COMMISSION

Disclaimer:

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GLOSSARY

Definitions

Term	Definition	Source
Platoon	A group of two or more automated cooperative vehicles in line, maintaining a close distance, typically such a distance to reduce fuel consumption by air drag, increase traffic safety by use of additional ADAS-technology, and improve traffic throughput because vehicles are driving closer together and taking up less space on the road.	
Platoon Level		
Requirement	Statement on what a system should achieve, should be able to perform.	Kick-off meeting
Specifications	Description of system properties. Details of how the requirements shall be implemented at system level	Kick-off meeting / IDIADA
Convoy	A group of two or more vehicles driving together in the same direction, not necessarily at short inter-vehicle distances and not necessarily using advanced driver assistance systems	
Truck Platoon	A truck platoon may be defined as trucks that travel together in convoy formation at a fixed gap distance typically less than 1 second apart up to 0.3 seconds. The vehicles closely follow each other using wireless vehicle-to-vehicle (V2V) communication and advanced driver assistance systems	Adapted from ACEA website

Acronyms and abbreviations

Acronym / abbreviation	Meaning
ACC	Adaptive Cruise Control
ADAS	Advanced driver assistance system
AEB	Autonomous Emergency Braking (System, AEBS)
ASN.1	Abstract Syntax Notation One
BTP	Basic Transport Protocol
C-ACC	Cooperative Adaptive Cruise Control
C-ITS	Cooperative ITS
CA	Cooperative Awareness
CAM	Cooperative Awareness Message
CCH	Control Channel
DEN	Decentralized Environmental Notification
DENM	Decentralized Environmental Notification Message

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DSRC	Dedicated Short Range Communications
ETSI	European Telecommunications Standards Institute
EU	European Union
FCW	Forward Collision Warning
FLC	Forward Looking Camera
FSC	Functional Safety Concept
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HARA	Hazard Analysis and Risk Assessment
HiL	Hardware in the Loop
HMI	Human Machine Interface
HW	Hardware
IO	Input / Output
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
ITS	Intelligent Transport System
LDWS	Lane Departure Warning System
LKA	Lane Keeping Assist
LCA	Lane Centering Assist
LRR	Long Range Radar
MRR	Mid Range Radar
OS	Operating system
ODD	Operational Design Domain
PAEB	Platooning Autonomous Emergency Braking
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V2X	Vehicle to any (where x equals either vehicle or infrastructure)
VDA	Verband der Automobilindustrie (German Association of the Automotive Industry)
WIFI	Wireless Fidelity
WP	Work Package

EXECUTIVE SUMMARY

CONTEXT AND NEED OF A MULTI BRAND PLATOONING PROJECT

Context

Platooning technology has made significant advances in the last decade, but to achieve the next step towards deployment of truck platooning, an integral multi-brand approach is required. Aiming for Europe-wide deployment of platooning, 'multi-brand' solutions are paramount. It is the ambition of ENSEMBLE to realise pre-standards for interoperability between trucks, platoons and logistics solution providers, to speed up actual market pick-up of (sub)system development and implementation and to enable harmonisation of legal frameworks in the member states.

Project scope

The main goal of the ENSEMBLE project is to pave the way for the adoption of multi-brand truck platooning in Europe to improve fuel economy, traffic safety and throughput. This will be demonstrated by driving up to seven differently branded trucks in one (or more) platoon(s) under real world traffic conditions across national borders. During the years, the project goals are:
Year 1: setting the specifications and developing a reference design with acceptance criteria
Year 2: implementing this reference design on the OEM own trucks as well as perform impact assessments with several criteria
Year 3: focus on testing the multi-brand platoons on test tracks and international public roads

The technical results will be evaluated against the initial requirements. Also, the impact on fuel consumption, drivers and other road users will be established. In the end, all activities within the project aim to accelerate the deployment of multi-brand truck platooning in Europe.

Abstract of this document

Deliverable 4.1 of project ENSEMBLE deals about the impact on infrastructure, namely pavements, bridges and tunnels. For both pavements and bridges, this impact will be assessed with help from field measurements and numerical simulations.

This document aims at gathering inputs for the part on the impact of platooning on tunnels.

1. QUESTIONNAIRE

1. Name, first name, email address of person filling in the questionnaire

2. Tunnel name (or other road infrastructure)

3. Geometry of tunnel

4. Number of tubes, diameters, number of lanes

5. Road alignment, longitudinal profile

6. Emergency places for trucks (and their geometry)

7. Current traffic management (trucks and light vehicles, other types of traffic)

8. What adaptation of traffic management if autonomous traffic (think about the autonomous traffic itself, and the other one –non autonomous–, and the other direction)

9. I2V: existence? technology? Content? (is there already I2V communication ? which technology would be prefered/installed ? what content for the messages would you advocate ?)

10. V2I : existence ? technology? Content? (is there already I2V communication ? which technology would be prefered/installed ? what content for the messages would you advocate ?)

11. Communication means in tunnel (what are the communication means in the tunnel, already installed or intended ? WIFI, 5G, ...)

12. Tunnel SHM or other monitoring

13. Issues linked to cross-border issues : different regulations, roaming, ...

18. Comments (for example, other encountered issues)