IMPACT ON INFRASTRUCTURE OF REDUCED LATERAL WANDERING OF CAV




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Abstract
Connected and automated traffic is currently planned, with reduced lateral wandering of vehicles within lanes. This is particularly a problem in the case of road freight vehicles whose axle loads are high, up to 13 tons in France, while in Europe, axle loads are limited to 11.5t (10.5 t) for drive axles (non-drive axles). In addition, the update of the European standard EC 96/53 proposes that the driving axle loads of zero-emission vehicles (ZEV) are increased to 12.5t.
Another driving characteristic to be taken into account for future assessment of traffic loads in the reduced lateral wandering of the CAV: having all vehicles traveling in the same lateral position implies a rail-type damage phenomenon with increased rutting and fatigue for both the pavement and bridges.
In the EU, there are approximately 5 million kilometres of roads, with a total value of over 8 000 billion euros. The circumstances mentioned above will negatively affect European road infrastructure and can lower the total value of the road owner's assets from a longer perspective. The road owner's perspective was added to the document.
Keywords: CAV, pavement, bridge, lateral wandering, advanced driver-assistance systems (ADAS); ZEV 12,5t driving axle (EC96/53 update draft).

1. Introduction

Freight is expected to increase in Europe (Figure 1, see [1]), where current ambition (CA) and high ambition (HA) refer to the two scenarios modelled by the OECD ITF, which represent two levels of ambition for decarbonizing transport. In particular, non-urban freight demand will increase by 52% between 2019 and 2050 under the High Ambition scenario and by 95% under the Current Ambition scenario.
Moreover, as the type of mobility might change (connected and automated vehicles, platooning, etc.), the impact of this increase of freight needs to be assessed taking into account new types of vehicles and new types of driving conditions.

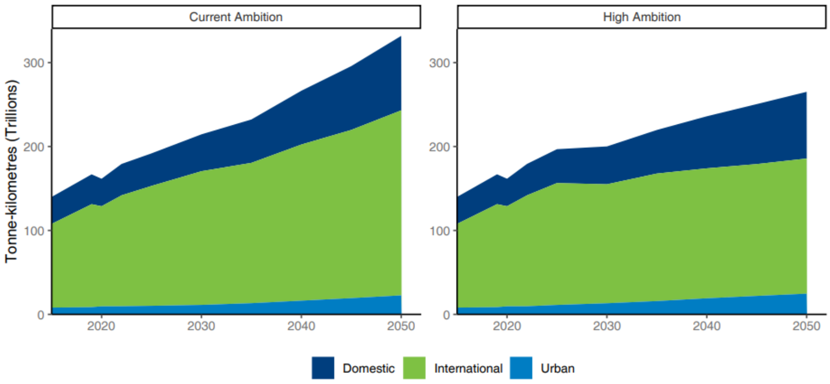

Figure 1: Freight grouped by activity type under current and high-ambition scenarios (from [1]).

Indeed, Connected and automated vehicles (CAV) will probably be first introduced over longer distances, with fewer safety concerns, therefore on the main road freight corridors (Figure 2).
Having all vehicles traveling in the same lateral position implies a rail-type damage phenomenon with increased rutting and fatigue for both the pavement and bridges.
Many activities leading to increased road freight transport, such as asset sharing and digitalization, may lead to a rebound effect, meaning that trade growth increases road freight The reason is that road freight transport will be cheaper, without the need to pay for a driver [2]. In terms of road infrastructure, several types of impacts need to be assessed: pavements, bridges, and other road assets will be affected by these changes in traffic regulations.

1.1 Bridges

Although bridges do not represent the largest surface in road networks, they are key points in road infrastructure that can become bottlenecks or even stops.

Current bridges have been designed for various regulations where even the latest ones (the Eurocodes) were calibrated in the 1990s, which implies that the design loads do not always cater to the current traffic loads.

The change in the impact of CAVs on bridges may be explained by the following factors: 1) higher drive axle loads (because of allowances for alternative fuel engines [3]), 2) reduced distance between vehicles (in case of platooning for example), 3) reduced lateral wandering, and 4) increased braking forces (because of closer vehicles). There are few results on the assessment of changes in the impact on bridges and their consequences in terms of finances and lifecycles of the structures. Therefore, the recommendation is to conduct more studies while analysing the possible mitigation possibilities of intelligent access.

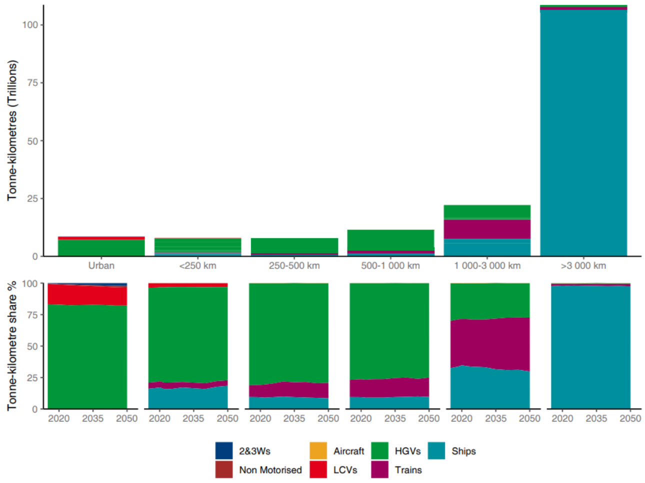

Figure 2: Freight demand in 2050 by travel distance (from [1]).

1.2 Pavements

As flexible pavements make up almost 95% of the world's roads [4], this study focused on this pavement type.

Several different existing studies [5], [6] in the world on the impact of CAV on elastic pavements induce some worries for road owners about the future roads, and from these different studies, it appears that CAV cause significant damage to elastic pavements in most cases, because the (axle) loads may be more localized.

In this article, some existing studies around the world are analysed from the point of view of road owners.

The risk is that if the CAV impact is high for the pavements (at a given time in the future) and road owners miss the optimum starting time to add extra strength to the calculation methods (Increasing E needed, MPa - calculated from ESAL's - Equivalent Single Axle Load's), it can take much more resources later. The same could be the case with ZEV (12,5t driving axle in the future) if adopted in EC 96/53. The CAV could also have then a 12,5t driving axle, so the impact of one extra ton is also analysed below.

Moreover, as in normal pavement design, the future 20-30 years predicted traffic load is taken into account, and we now need to have some elements about the predicted 2045-2055 traffic loads and the associated load models.

The most critical places are usually urban streets: there are culver stones, and the addition of asphalt layers on top of them is generally not an option to compensate for the lack of strength.

For the pavements, some recommendations are given in the conclusion, that is, the need to standardize in Europe (or the world) and traffic management procedures (minimal wandering and minimal distances between trucks) depending on the recorded temperature.

2. Impact to Bridges

The impact of CAVs on bridges can be decomposed into several subpoints: 1) the impact of changes in the layout of the vertical forces on the structure, 2) the reduced lateral wandering effect as CAVs control and impose a given lateral wandering pattern, and 3) the horizontal (braking) forces, which may increase if CAVs are traveling closer to each other.

These points have been treated in a small way in the literature, sometimes through the lens of the platoons. Other points might be of interest, such as the dynamic impact of the CAVs of bridges (modal behavior), which have been extensively studied for railways and trains [7].

2.1 Vertical forces

As stated by Sayed et al. (2020), there is not much literature on the impact of platoons on bridge preservation. The findings already available in the literature deal only with the impact of closer vertical loads and increased braking force.
Taking into account the vertical forces, static calculations show that for some types of bridges, the loads on the infrastructure will increase (see Figure 3). This increase in the effect in bridges might lead to loads higher than the notional live loads (see Figure 4).

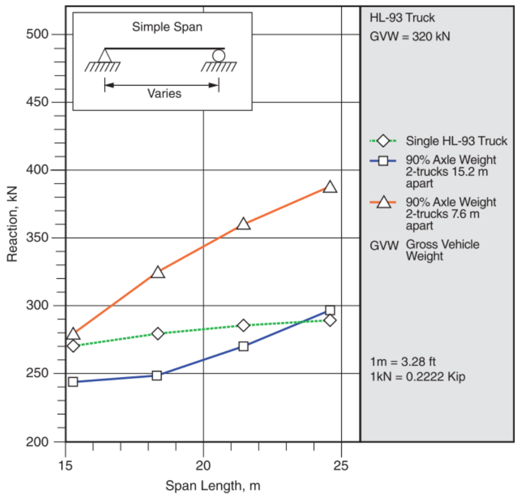

Figure 3: Reaction forces for a simply supported span and various truck configurations. Extracted from [8].

In particular, as has been studied by ([9] and [10], the effects of truck platoons might exceed the design loads (loads that are given in the standards and which are used to design the bridges), which brings about the need to verify the load models and perhaps again calibrate these load models. In the USA, this would mean working 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, as defined in the Eurocodes [11], [12].

These changes reflect the fact that the introduction of truck platooning will bring about new load situations [13], with closer moving loads and less lateral wandering.

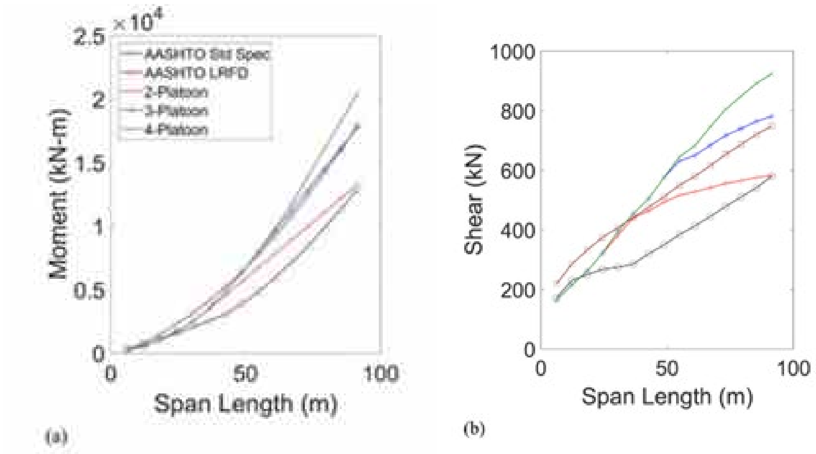

Figure 4: Simple span results of the 6.1-m platoon for (a) positive bending and (b) shear force. Extracted from [10].

2.2 Reduced lateral wandering

Reduced lateral wandering is an issue for some bridge structures. While the Eurocodes propose a lateral wandering of 20 cm from the middle of the road, real measurements show a variety of situations [14]. However, all of these situations are more favourable than the rail-type, in-line application of moving axle loads of trucks because the loads are distributed more widely in the lateral direction.

2.3 Braking forces

The brake forces of platoons have also been identified as potential problems [15] and simulated through a complete truck-bridge modelling procedure. Here again, it has been shown that the number of trucks within a platoon is a key parameter in determining the speed of traffic.
Furthermore, this type of design method is valid for new structures but does not address the problem of older, existing structures [16] whose structural health is unknown and that already has problems in dealing with current traffic loads.
Therefore, many truck parameters influence the potential impact of platoons on bridges, namely the number of trucks, the gap between them, and the driving speed, which indicates the need for the development of regulations and advice for truck operators, logistics, and service providers.

2.4 Recommendations

Regarding the increased impact of some heavy CAVs on bridges on the fact that bridges are built for a design life of at least 100 years, there is a need to preserve this infrastructure stock and the safety of people that could be linked to it.
For that, the recommendation for the management of CAVs would be to create levels of impact, and therefore, individual groups of CAVs for which specific traveling rules apply:

- The first category concerns CAVs which would not bring about more negative impact on bridges: for this, the rule for passing the infrastructure could be similar to those of the "normal" (conventional, according to the regulations) traffic;
- The CAVs that induced a higher impact on the bridges but did not endanger the structure (by taking into account the safety margins including the reassessment procedures) should be allowed to pass through the structure but have to contribute to the maintenance and repair actions that become necessary because of these higher impacts. This could

consider the shape of bridge tolls, or more generally network tolls, by taking into account other impacts.

- There might be CAVs that pass over the structure endangering the structural integrity of the bridge, and different traffic rules need to be derived; for platoons, the solution might be to dissolve the platoon locally in the neighbourhood of the structure. For the other CAVs, including those that are predicted for the future, detailed assessment muss be done, and strengthening of the structures might be the solution.

These recommendations are about CAVs because of that seems the long-term feature, but the reduced lateral wandering problem is an issue for all levels of automation: even low level of automation incorporate lane keeping feature, which induce higher damage levels [17].

3. Impact on Elastic Road Pavements

Different studies around the world on the impacts of CAVs on infrastructure and ZEV have been analysed shortly below, from the point of view of the road owner's pavement specialist.

In Europe, there are roughly 5 million kilometres of roads, with a total value of approximately 8 000 bill EUR, according to ERF statistics.
As pavements represent approximately half of the total cost of road infrastructure, road owners are paying considerable attention to this asset.

Even in a small country like Estonia, where there are only 0,04 million kilometres of highways with an estimated value of approximately 5 billion euros, road owners are still worried about every new type of load impact that might significantly damage the pavements.

In the current state of infrastructure and regulation in Estonia, CAVs could theoretically drive on specific pavement marking sections, which represent approximately 3,000 km out of 17 000 (approximately 18%).

The scientific and technical literature describes circumstances around CAVs that negatively affect the EU road infrastructure and may lower the total value of road owners' assets by 5% to 25% from a longer perspective, depending on what kind of traffic load is allowed in the future on European roads.

The causes of wandering in traditional driving conditions compared with autonomous driving were considered.

3.1 Autonomous vehicles wheel wander: Structural impact on flexible pavements

[6] provides an overview and the results of four different studies conducted worldwide between 1999 and 2019. This statistic gives road owners a good insight that the negative impact of CAV on pavements should be paid more attention.

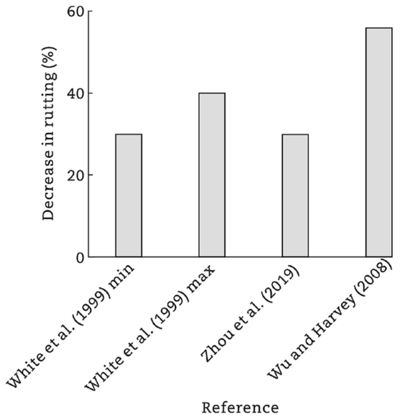

Figure 5: Impact of wheel wander on rutting[6].

The decrease in rutting varies between 30% and 56% in the case of human driving compared to the zero-wheel wander of autonomous trucks (Figure 5).

The increase in the acceleration rate of fatigue damage ranged from 2 to 3 in the case of channelized traffic with respect to the normal distribution of traffic. This implies that the service life of pavements is reduced by a number between two and three.

These numbers mean that the impact of CAVs on elastic pavements and maintenance cost might be very high if there is no standardized optimal wheel wander distribution (as the study points out its need).

3.2 Effect of different platoon configurations on strains and fatigue performance of flexible pavements

[5] is based on field tests and data modelling. It is clear that CAVs have a significant impact on pavement life if they are not regulated (considering the maintenance of road owner assets and CO^2).

The parametric study mainly analysed the influence of inter-truck time gaps and lateral wander on the impact of platoons on pavement strains and pavement fatigue. The **first** result of the study is that without special precautions (with short inter-truck time gaps of 0.5 s and no lateral wandering), platoon loading can increase pavement fatigue. At maximum, in the parametric study, a reduction in fatigue life of 79 % was obtained with a 0.5 s time gap and at 35 °C. The second important result is that the impact of platoons on pavement strains and fatigue depends on the pavement temperature. At low to intermediate temperatures (15 °C in this study), the increase in strain due to the platoons is very small because the accumulation of strain under multiple loads due to viscoelasticity is very limited. At high pavement temperatures (35 °C in this study), the viscoelastic effects become much more important, and multiple loads, with short rest periods, owing to platoons increasing asphalt strains (and therefore pavement fatigue), compared with single trucks.

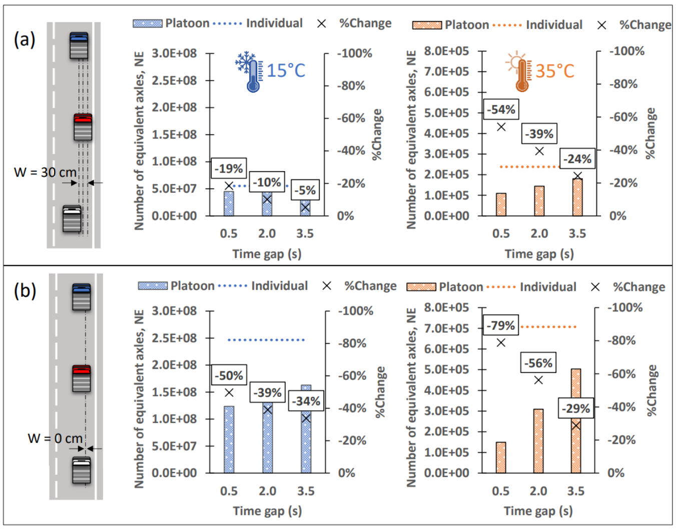

Figure 6: Pavement service lives expressed in the number of equivalent axles (NE) for 3-truck platoons at 80 km/h. [5]

The research results clearly show the service life of pavement reduction in percentage (Figure 6). It is easy to estimate to the road owners that such CAV vehicles on your roads could damage the same amount of your pavement assets; for example, -50% (15ºC, 0,5s, see Figure 5) means that i.e. a 1-billion-euros European pavement asset does not live anymore 20 years, but 10 years with change from the human drivers to the CAVs from a longer perspective. Therefore, the road owner needs twice the investment (option 1 – act passively).

The **second** (act proactively) option is to start building much thicker pavements – this is cheaper than maintaining two shorter periods, but needs to react many years or decades earlier than the CAVs are massively driving on the pavements.

In the future it is possible also the **third** option (act smart & proactively) - to consider and develop Intelligent Access (IA). It is technically possible to develop standards that determine for the CAV producers the optimal wheel wander distribution, space between CAVs, etc., depending on the temperature as well as weaker infrastructure points (bridges, tunnels, etc.). With tools such as Smart Road maps [18], it is possible for CAVs to minimize their impact on road infrastructure by adapting their driving behavior.

In the CEDR Road Freight Transport Working Group, IA has been highlighted as a possible solution [19], as Intelligent Access is part of the digital transformation of road freight transport.

3.3 CAV with 12,5t ZEV driving axle impact on elastic pavements

As there is strong interest of the European heavy vehicle industry to rise the driving axle load from the existing 11,5t to 12,5t (for the ZEV vehicles and busses in 96/53/EC), many road owners are concerned of the impact of the one additional tonne.

The impact was estimated using the USA AASHO Road Test [20]. A total accumulation of 1 114 000 axle-load applications were attained, turning the 25-month traffic testing period. To accomplish this, soldiers of the U. S. Army Transportation Corps Road Test Support Activity drove more than 17 million miles. This resulted in a relationship between elastic pavement design and axle load applications. Thickness Index (**TI**) was determined (Figure 7).

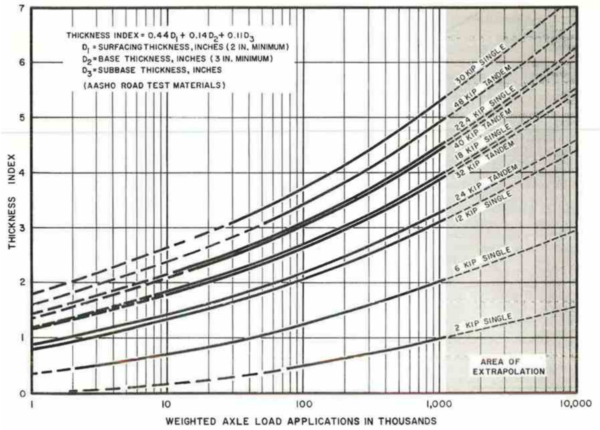

Figure 7: Main factorial experiment and relationship between design and axle application [20].

By converting the single axles from Figure 7, we converted the research results to the SI system in kN (Table 1). The tests were made ranging single axles between 2 to 30 KIP (so from 0.91 to 13.60t). The same procedure was followed for tandem axles.

Table 1: Thickness Index (TI).

KIP, Single	Single Axle, kN	Single Axle, t	Thickness Index (1 mln axles)	Thickness Index (10 mln axles)
2	8.9	0.91	1.00	1.70
6	26.7	2.72	2.00	3.00
12	53.4	5.44	3.20	4.40
18	80.1	8.16	3.90	5.70
22.4	99.6	10.16	4.60	6.30
30	133.4	13.60	5.30	7.30

When plotting these results (Figure 8), a good correlation (R^2) between the data was observed.

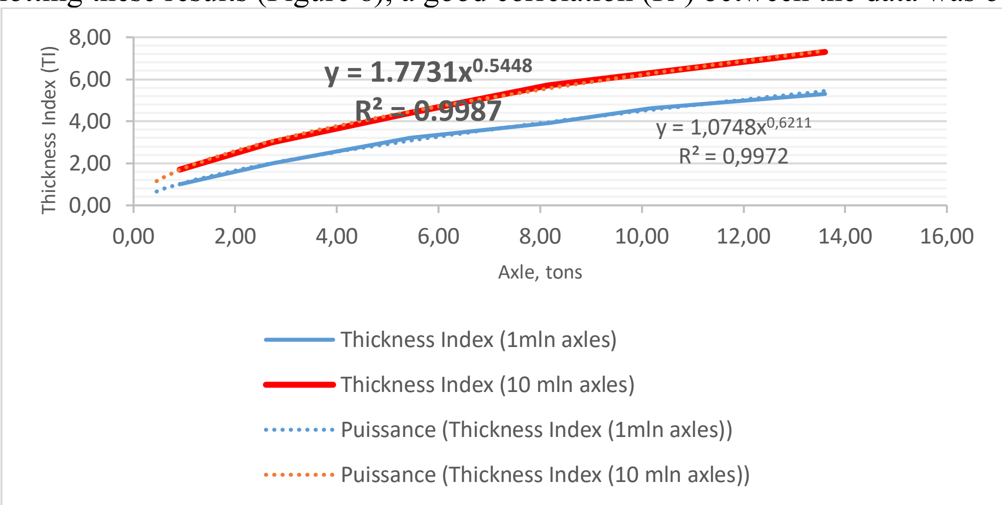

Figure 8: Single-axis SI load versus Thickness Index (TI).

This formula was used to calculate the TI value for any ton (Table 2).
It is easy to compare the TI growth between axle loads in the SI system.

Table 2: Thickness Index growth calculation for samples.

Single Axle, tons	TI, 10mln Single axles (R2 =0.9987)	TI growth comparisons
1	1.77	
2	2.59	
3	3.23	
4	3.77	
5	4.26	
6	4.71	10.4% (from 5 to 6t)
7	5.12	
8	5.50	
9	5.87	6,6% (from 8 to 9t)
10	6.22	
11	6.55	5.3% (from 10 to 11t)
11.5	6.71	
12	6.87	
12.5	7.02	4.6% (from 11,5 to 12,5t)
13	7.17	

We can see that loading the single axle from 11,5t to 12,5t, the TI is growing by +**4,6%**. TI is growing twice more (**10,4%)** if we load a single axle from 5t to 6t.

If the additional one-ton axle load is not correctly compensated in ZEV's, or the road owners do not have enough time and resources to build thicker pavements for ZEV's, they will have higher maintenance costs in the future.

In the fourth power law, an additional one ton load on an 11,5t (driving) axle means c**a 40% stress increase** to the existing pavement (Table 3). For example, in the case of a 2-axle ZEV bus, 40% more stress (ESAL's) will be generated in elastic pavements. The impact of the ZEV 2-axle bus vehicle is increasing by over 30%.

Table 3: Fourth power law.

Axle load, t	Ratio to 10t standard axle	In 4th Power: axle load impact
10	1.00	1.0
11.5	1.15	1.7
12.5	1.25	2.4
	Increase from 11,5t to 12,5t:	0.69
	Additional ESAL (stress) on the roads:	40%

In the fourth power law, an additional one ton load on an 8t (i.e trailer's tridem axle average) means **a 60% stress increase** to the existing pavement. ZEV 5-axle vehicle average stress could rise over 40% on 4th power law.

Road owners can compensate for the increase with building thicker pavements in the right time ahead, taking into account TI growth needs (see Table 2).

Further detailed studies and field tests are needed as the impacts might be very high (specially CAV's combined with ZEV in the future – damage effects are adding then together) and expensive for infrastructure owners, especially if it is not taken into account in the right time ahead (what can be decades at the road network level).

4. Conclusions

This study has been taking into account the changes in driving conditions of CAVs, while CAVs will need to be ZEVs because of regulations .

- Further studies at the European level are needed to understand the impact of the various new types of vehicles and their driving conditions to minimize the negative impact on the expensive infrastructure while staying on the decarbonization course.
- European standards should deal with new types of vehicles such as CAVs. From the road owner's point of view, one option is to standardize for the very smooth minimum wandering amplitude of CAVs and the minimum space between each other, depending on external conditions (weather, surrounding traffic, etc.).
- It can be considered to standardize temperature-dependent Intelligent Access (IA) regulation because elastic pavements are very sensitive to higher load concentrations, mostly at higher temperatures. IA makes it technically possible to maintain longer CAVs distances for weaker infrastructure elements (such as bridges) if road infrastructure information is used.
- If there is no European standard, then the road owners need to know in early stages how much they need to increase the pavement construction thicknesses to compensate for future load concentrations.
- It would be good to consider in Europe also to develop common Pavement Design Tool (AI based) and method to take account: predicted new loads, changing climate, new materials, etc.

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