HIGH-CAPACITY TRANSPORT IN CITIES AND THE IMPACT ON THE ROADS



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Abstract

This paper presents the evaluation of the relative pavement damage caused by a high-capacity transport (HCT) 5 axle truck with respect to three other reference trucks consisting of 4, 3 and 2 axles. The analysis was conducted by simulating the responses of three pavement structures using the pavement analysis tool ERAPave. Two damage criteria of the pavement structures were evaluated: fatigue cracking of the asphalt concrete (AC) layer and permanent deformation of the subgrade. The relative damage caused by the different vehicles were estimated by calculating a damage factor (D_r) following the Asphalt Institute Method. Three loading scenarios of the trucks were analyzed: (a) one way trip with fully loaded trucks, (b) round trip where the return trip consisted of the empty vehicles with lifted axles and (c) round trip where the return trip consisted of the empty vehicles without lifting any axles. The damage factors were calculated for per ton of carried load and were normalized with respect to the 2-axle truck. Results indicate that the relative impacts of the vehicles depend on the structure type and seasons. Generally, the 4-axle truck appeared to be the least damaging one. The HCT 5-axle truck is more damaging than the 4-axle truck, but less damaging than the other two.

Keywords: High-capacity transport, pavement damage, damage factor, fatigue cracking, subgrade rutting, axle load, payload, fuel consumption, emissions

1. Introduction

The construction industry is responsible for about 40% of energy use and one third of the greenhouse emissions world-wide (Fredriksson et al., 2021). Sezer and Fredriksson (2021) estimated that about 10% of these emissions stem from the transport of mass in connection with constructions. Thus, increasing efficiency of construction transport by improved logistic solutions and more efficient vehicles is of vital importance.
Roughly 20% of the Swedish goods transport relate to construction and infrastructure projects, but in urban areas as much as 50% weight-restricted transport is connected to constructions (Cederstav et al., 2022). To address the need for more efficient construction transport in cities, a pilot project on using high-capacity transport (HCT) vehicles for excavated material in urban areas in Sweden started in spring 2021. The project is called HCT City and includes partners from industry, city planners, universities, and research institutes. The term HCT is used to refer to heavy vehicles which are heavier/longer than the existing vehicles on the road network, allowed by regulations.

The roads in Sweden are divided into four classes of bearing capacities (called BK classes in Sweden). The allowed weight of the vehicle on each road depends on the distance between the first and last axle of the vehicle and the bearing capacity class of the road. The maximum allowed gross weight is 64 ton for BK1, 51.4 ton for BK2, 37 ton for BK3, and 74 ton for the recently added class of BK4 (Swedish Transport Agency, 2018). The maximum allowed length for heavy vehicles is 25.25 m, but there are plans to allow longer vehicles up to 34.5 m on part of the road network. Within several cities in Sweden, local restrictions on the weight and length of heavy vehicles exist. A common restriction in inner cities is a maximum length of 12 m and bearing capacity of BK2 which implies in practice a maximum weight around 25 ton for a truck where the distance between its first and last axles is around 7 m (Treiber and Bark, 2018).

In the HCT city project, two construction sites are used as pilots, one of which is in Stockholm, where excavations are going on for a new residential area. Specially designed 5-axle trucks with gross weight of 38-42 tons and a length under 12 m will be used for transport in connection to this site. That means the payload capacity will be doubled in comparison to common 3-axle trucks complying with the BK2 bearing capacity. According to an earlier study, such a solution has the potential of reducing fuel consumption by 50% (Treiber and Bark, 2016). However, there are concerns about the impact of the HCT 5-axle trucks on road wear. Therefore, as part of the project, a simulation study on the effects of HCT 5-axle truck on the road wear, in comparison with three reference trucks has been performed. Three pavement structures relevant for Stockholm urban area were used in the simulations, and two critical seasons of spring thaw and summer were considered. The outcomes of this study are presented and discussed in this article.

2. Methodology

The objective of this work is to compare the risk of pavement damage induced by the HCT truck with three reference trucks, shown in Figure 1. The study was carried out by simulations using a pavement analysis tool called ERAPave (Elastic Response Analysis of Pavements), developed by the Swedish National Road and Transport Research Institute (Erlingsson and Ahmed, 2013; Ahmed and Erlingsson, 2015). Three hypothetical pavement structures, relevant to Stockholm urban area, were analyzed. These three structures comprised of asphalt concrete (AC) layers with different thicknesses (relatively thin, intermediate, and relatively thick) to cover the possible variations that may be encountered along the route of the trucks. The analysis was carried out for two critical seasons: (a) the spring thaw period, and (b) summer. Layer and material properties of the pavement structures required for the analyses were based on typical values determined from laboratory tests and historic data.

The analyses were conducted considering the viscoelastic behavior of the AC materials whereas the unbound layers were assumed to follow a linear elastic behavior. The vehicles were modelled using the axle load and spacing, tire pressure, tire configuration and speed. For each passage of the vehicles, the stresses and strains developed in the different layers were calculated and the relative damages caused by the different vehicles were evaluated and compared. Three scenarios for the loading of the trucks were analyzed: (a) one way trip with fully loaded trucks, (b) round trip where the return trip consisted of empty vehicles with lifted axles and (c) round trip where the return trip consisted of empty vehicles with all axles on the ground.

2.1 Description of the trucks

The HCT truck has 5 axles, is 10.75 m long and can carry 23.5 tons of load. The reference trucks have 2-4 axles, are 7.08-8.66 m long and can carry 7-18 tons, see Figure 1. The HCT truck has an extra steerable axle at the front, about 2 m behind the front axle. Other relevant parameters of the trucks and their tires are listed in Table 1.

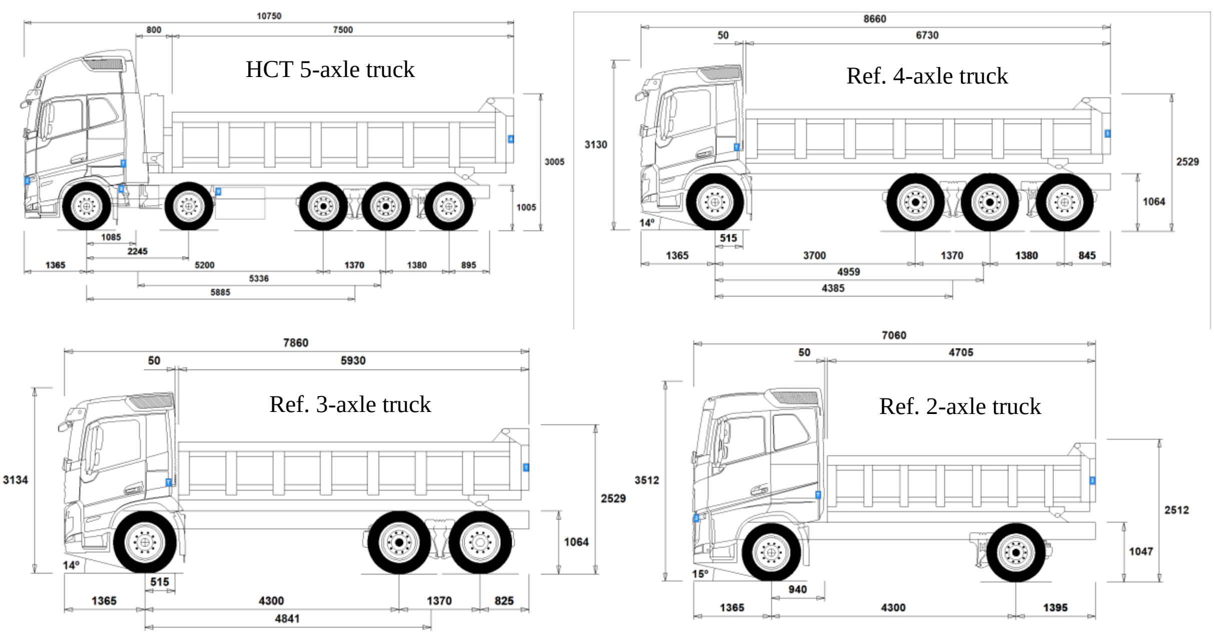

Figure 1 – Schematic picture of the HCT truck and the three reference trucks

Table 1 – Relevant parameters of the trucks

Description	HCT 5 axle truck					Ref. 4 axle truck				Ref. 3 axle truck			Ref. 2 axle truck	
	Axle 1	Axle 2	Axle 3	Axle 4	Axle 5	Axle 1	Axle 2	Axle 3	Axle 4	Axle 1	Axle 2	Axle 3	Axle 1	Axle 2
Tire type	Single	Single	Dual	Dual	Single	Single	Dual	Dual	Single	Single	Dual	Single	Single	Dual
Tire pressure (Bar)	9	9	8	8	9	9	8	8	9	9	8	9	9	8
Axle type	Steered	Steered	Driven	Driven	Steered	Steered	Driven	Driven	Steered	Steered	Driven	Steered	Steered	Driven
		Liftable			Liftable				Liftable			Liftable		
Tire size	385/65	385/65	315/80	315/80	385/65	385/65	315/80	315/80	385/65	385/65	315/80	385/65	385/65	315/80
Axle load (loaded vehicle)	9 t	9 t	8.4 t	8.4 t	7.2 t	9 t	8.4 t	8.4 t	7.2 t	9 t	8.7 t	5.8 t	8 t	10 t
Axle load (empty vehicle) (lifted axles)	8 t	Lifted	5 t	5 t	Lifted	5.5 t	4.75 t	4.75 t	Lifted	4.7 t	7.3 t	Lifted	5 t	6 t
Axle load (empty vehicle) (no lifted axles)	4.5 t	4.5 t	3.15 t	3.15 t	2.7 t	6 t	3.1 t	3.1 t	2.8 t	5.6 t	3.9 t	2.6 t	5 t	6 t
Gross weight	42 t					33 t				23.5 t			18 t	
Empty weight	18 t					15 t				12 t			11 t	
Carried load	24 t					18 t				11.5 t			7 t	

2.2 The pavement structures

The relative impacts of different vehicles on a pavement structure are dependent on the mechanical properties of the structure itself. For this reason, three typical structures were analyzed to cover the possible range of road structures in Stockholm area that may be encountered by the vehicles of this study. Since the mechanical properties of pavements vary with season (due to variation in temperature and moisture), two critical seasons, that is the spring thaw period and the summer, were considered. During the spring-thaw time, the air temperature is relatively low. So, the upper AC layers of pavements are relatively stiff. But the melted ice in the bottom layers increases the moisture contents of the subgrade and the unbound base and subbase layers. This results in lowered stiffnesses of these layers. On the other hand, during the summer, the air temperature is relatively high resulting in lowered stiffnesses of the AC layers. However, the moisture content during the summer is generally much lower in the subgrade and the base and subbase layers which makes them relatively stiff. Thus, these two seasons represent two opposite scenarios and hence were considered for this study.

The thicknesses and the types of materials of each layer of the three structures are presented in Figure 2. The mechanical properties of the layers, required for the analyses, were estimated based on existing laboratory test results and recommended values by the Swedish Road Administration (Trafikverket, 2011). These are presented in Table 2. For the analyses, the average temperatures of the AC layers were assumed to be 10°C during the spring and 25°C during the summer. Since AC is a viscoelastic material, the viscoelastic parameters of the AC layers were considered for the analyses. The material properties for all these three structures were assumed to be identical. The difference was in the layer thicknesses. Structure 1 had a relatively thick (20 cm) AC layer, and a thicker unbound base layer (10 cm vs 8 cm) but a thinner unbound subbase layer (30 cm vs 42 cm) compared to Structure 2 and Structure 3. The difference between Structure 2 and Structure 3 was in the bituminous base layer thickness only. The AC layer thickness of Structure 2 was 15 cm while Structure 3 had a relatively thin AC layer of 10 cm.

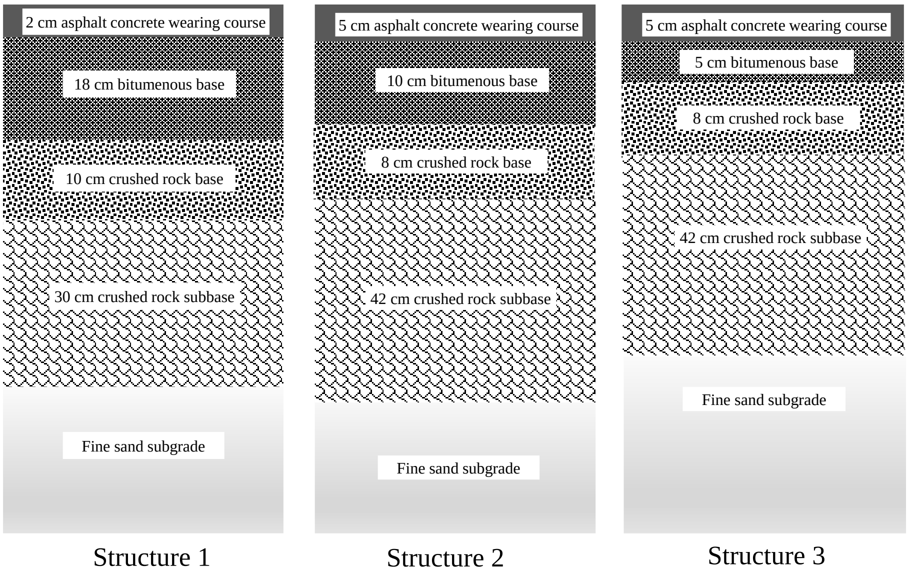

Figure 2 – The three road structures analyzed, representative of Stockholm urban area

Table 2 – Assumed material properties of the different layers of the structure

Layer		Asphalt concrete wearing course		Bituminous base course	Crushed rock base	Crushed rock subbase	Subgrade
Spring	Elastic modulus [MPa]	-		-	200	100	35
	Viscoelastic parameters	D_0	0.0000505	0.000051	-	-	-
		D_1	0.000445	0.000583	-	-	-
		m	0.346	0.312	-	-	-
Summer	Elastic modulus [MPa]	-		-	300	150	100
	Viscoelastic parameters [-]	D_0	1.47E-07	0.0000506	-	-	-
		D_1	0.00127	0.00155	-	-	-
		m	0.312	0.337	-	-	-

2.3 Analysis using ERAPave

The study was carried out in ERAPave by simulating the responses of the three pavement structures due to the passage of the four trucks. ERAPave is an axi-symmetric layered visco-elastic theory-based pavement response analysis tool. Axi-symmetric implies that the contact area between the tire and the pavement surface is assumed to be circular. Using ERAPave, the stresses and strains induced in different layers of a pavement due to moving traffic load can be calculated.

In ERAPave, the three pavement structures were modelled based on their layer thicknesses and material properties (during the spring and the summer). The vehicles were modelled using their respective axle loads and configurations, tire pressure and speed. The distances between the wheels and wheel types (single or dual tires) were used as inputs using a coordinate system, presented in Figure 3. For the calculations, half axle loads (that is, wheel loads) were used. A reference speed of 45 km/hour was considered which mostly affects the viscoelastic behavior of the AC layers. Using the pavement and vehicle models in ERAPave, the stress and strain induced in the different layers of the structures were calculated.

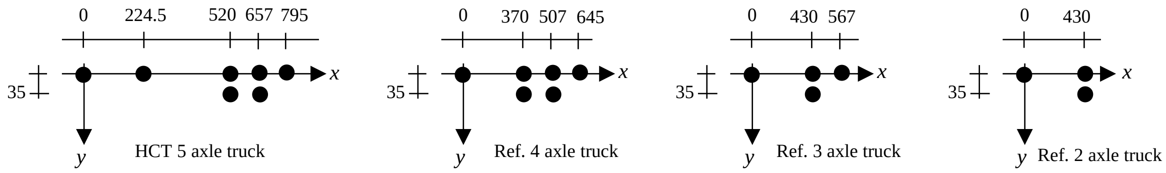

Figure 3 – The coordinate system used in ERAPave for the wheels of the four trucks studied (units are in cm)

3. Results and discussions

For pavement analysis and design, two of the most common types of damages taken into consideration are the fatigue cracking of the AC layer and the permanent deformation of the subgrade (subgrade rutting). The fatigue cracking of the AC layer, also known as bottom-up cracking, occurs in proportion to the induced tensile strains at the bottom of the AC layers, mostly in the transverse direction. On the other hand, the subgrade rutting is dependent on the magnitude of the vertical strain on the top of the subgrade layer. In this study, these two failure modes of pavements were analyzed.

Using ERAPave, the transverse strains induced at the bottom of the AC layers and the vertical strains at the top of the subgrade of the three structures due to the passages of the four vehicles were calculated. Examples of the calculated strain responses in Structure 1 and 3 during the spring for the four vehicles are shown in Figure 4 and 5. In these plots, the amplitude peaks at a certain point of the structures caused by the passing of the different axles of the vehicles can be seen. The viscoelastic responses of the AC layers are manifested by the delayed dwindling of the peaks as the wheels passed over that point.

The relative damage of the AC layer and the subgrade caused by the different vehicles can be calculated based on the Asphalt Institute Method (Huang, 2004). According to the AC fatigue criterion, the allowable number of load repetitions to control bottom-up cracking can be expressed as

$$N_t = a_t(\varepsilon_t)^b \tag{1}$$

According to the permanent deformation criterion, the allowable number of load repetitions to control permanent deformation of the subgrade can be expressed as

$$N_v = a_v(\varepsilon_v)^b \tag{2}$$

where, N_t and N_v are the allowable number of load cycles for AC fatigue cracking and subgrade rutting, respectively. ε_t is the transversal tensile strain at the bottom of the AC layer, ε_v is the vertical compressive strain at the top of the subgrade and a_t, a_v and b (b is usually taken as -4) are material constants.

The damage ratio (*D*) for a pavement structure is defined as a sum of the ratios between the predicted number of load repetitions n_i and the allowable number of load repetition N_i for load *i* (*i* = 1, 2, … *m* where *m* is the total number of load cases) calculated using Equation (1) or (2) as follows:

$$D = \sum_{i=1}^{m} \frac{n_i}{N_i} \tag{3}$$

To compare the damage risk caused by a vehicle with respect to a reference vehicle, a relative damage factor (D_r) can be defined as the ratio between their respective damage ratios. Thus, in this study, the damage factors for the different vehicles were calculated in relation to the reference 2-axle vehicle, computed as:

$$D_r = \frac{D_j}{D_2} = \frac{(\varepsilon_1^4 + \varepsilon_2^4 + \cdots + \varepsilon_j^4)_{j-axle\ truck}}{(\varepsilon_1^4 + \varepsilon_2^4)_{2-axle\ truck}} \tag{4}$$

where, D_2 and D_j are the damage ratios for the 2-axle vehicle and the vehicle with *j* number of axles, respectively. ε_k is the magnitude of the peak strain corresponding to the *k*-th axle (*k* = 1, 2, … *j*) of the vehicle.

Two damage factors can be defined for the two failure modes: (a) for AC fatigue cracking and (b) for subgrade rutting. For any vehicle, $D_r < 1$ means that the vehicle is less damaging than the 2-axle vehicle and $D_r > 1$ means that the vehicle is more damaging than the 2-axle vehicle. For the 2-axle truck, D_r is equal to 1.

Since the load carrying capacities of the vehicles are different, they will require different numbers of trips to carry the same amount of goods. Thus, for fair companions, the damage factor of each vehicle was divided by their individual load carrying capacity, giving values of the damage factors per ton of carried load. Furthermore, the damage factors per ton of carried load were normalized by dividing those values by that for the 2-axle vehicle to get a better perception of their relative damage potentials. For the round trips, two scenarios were considered. One scenario was when the vehicles returned empty without lifting any of the axles and the other scenario was when the vehicles returned empty with lifting the liftable axles (see Table 1). For the return trips, the damage factors were calculated in a similar manner. For calculating the damage factors for the round trips, the damage factors for the loaded state and unloaded state were added together and divided by the individual load carrying capacity and were normalized with respect to the 2-axle vehicle. The calculated D_r values for all the analyzed conditions are presented as bar charts in Figures 6 and 7.

From Figure 6 and 7, it is observed that the damage factors for the different vehicles vary depending on the structure types and seasons. It should be noted that these plots represent the relative damage risks (normalized) of the vehicles with respect to the 2-axle truck. The values do not represent which structure or season is more prone to damage.

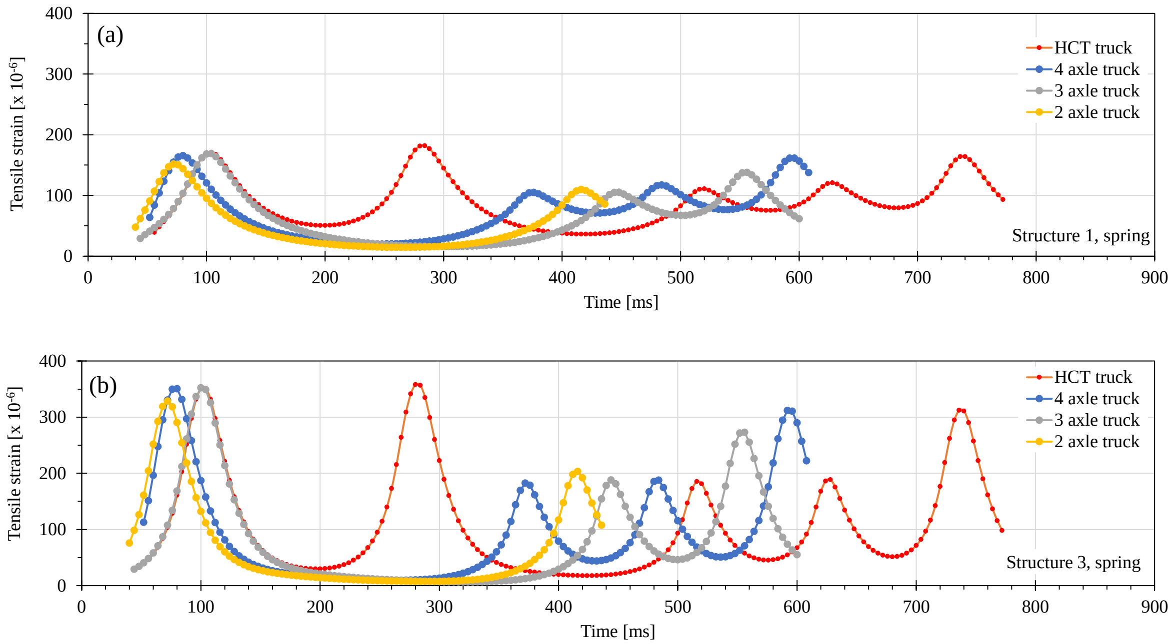

Figure 4 – Transverse tensile strains at the bottom of the AC layer due to single passage of the fully loaded vehicles in springtime: (a) Structure 1 (b) Structure 3

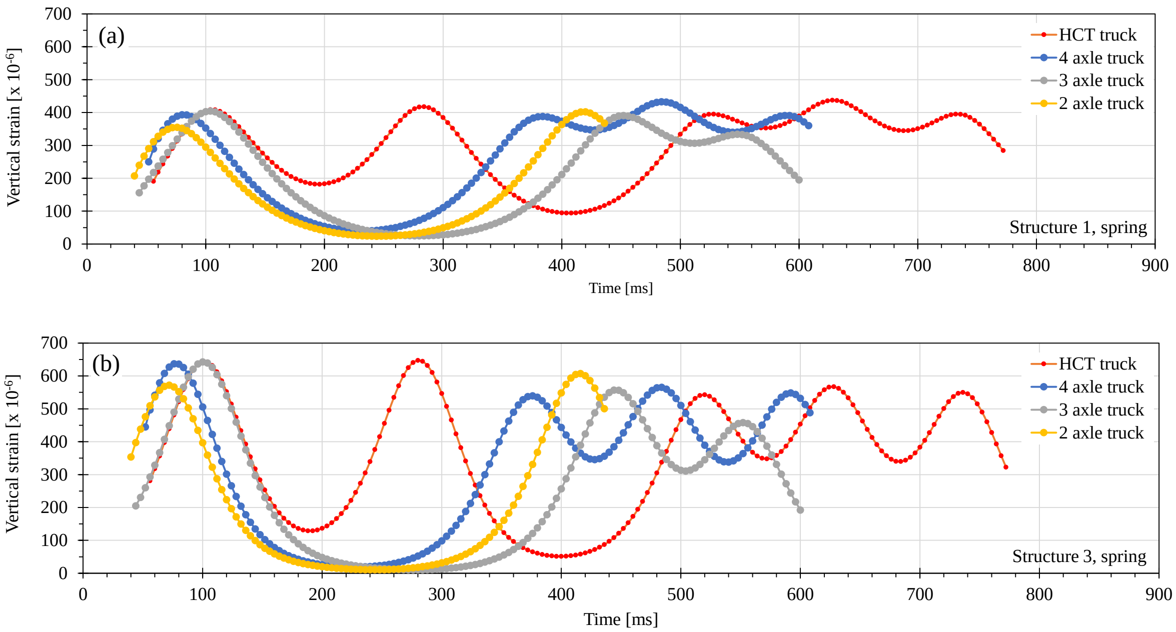

Figure 5 – Vertical strains at the top of the subgrade due to single passage of the fully loaded vehicles in springtime: (a) Structure 1 (b) Structure 3

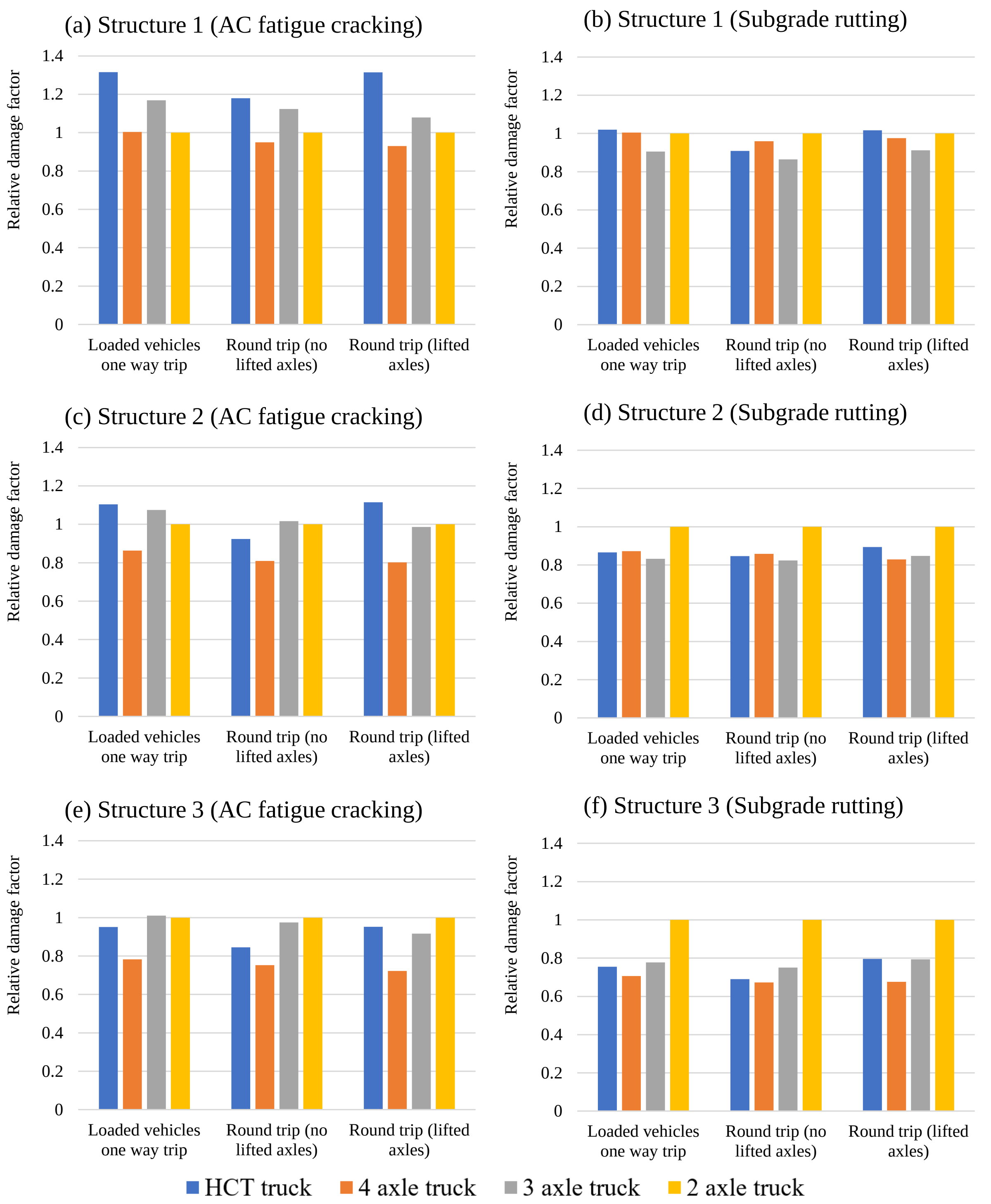

Figure 6 – Relative damage factors (per ton of carried load) of the different trucks with respect to fully loaded 2 axle truck (during the spring)

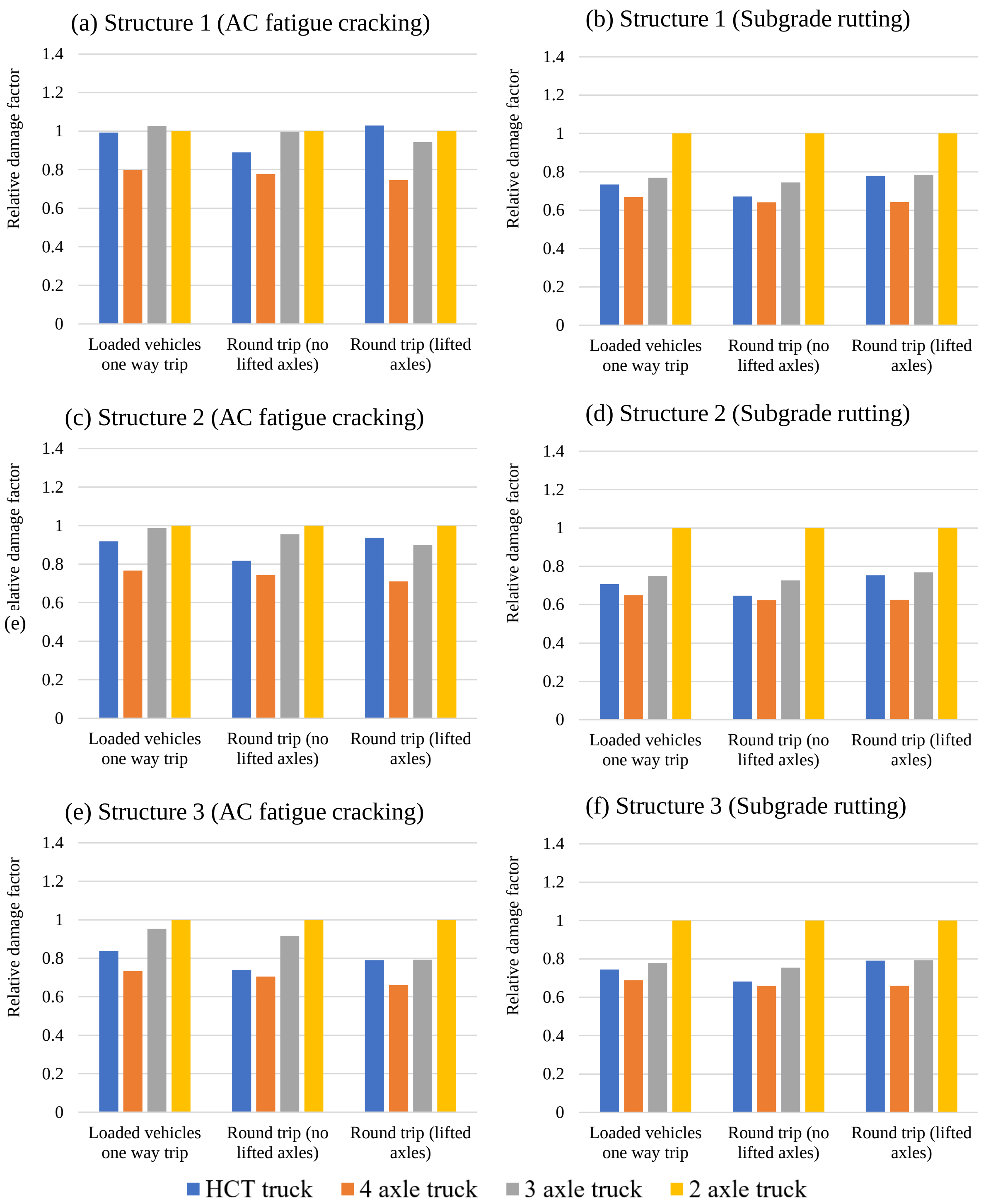

Figure 7 – Relative damage factors (per ton of carried load) of the different trucks with respect to fully loaded 2 axle truck (during the summer)

For AC fatigue cracking, the 4-axle truck has the lowest D_r value in all cases, meaning that it will cause the least damage to the AC layer compared to the other vehicles. For subgrade rutting, the 4-axle truck is again the least damaging one for most situations. Only during the spring, the 4-axle truck appears to be relatively more damaging to the subgrade for structures 1 and 2 while the 3-axle truck is then the least damaging one (the differences are quite small). The HCT truck is more damaging than the 4-axle truck in most of the cases (exceptions are during the springtime for subgrade rutting for structure 1 and 2 for the round trip with no lifted axles). The relative damage to the AC layer caused by the HCT truck is higher than that of the 3-axle and 2-axle trucks for structures 1 and 2 during the spring. For subgrade rutting, the HCT truck is less damaging than the 3-axle and 2-axle trucks in most of the cases. Although the relative damage factors indicate that the HCT truck can be more damaging to the AC layers compared to the 3-axle and 2-axle trucks (springtime, structure 1 and 2), this may be less significant since the induced strains are lower (Figure 4) for these scenarios. The reason is that the AC layer is stiffer during the springtime and structures 1 and 2 are relatively thick.

The HCT truck and the 4-axle truck are similar in configuration. The HCT truck has an additional single axle mounted with single wheels to carry the additional load. By this, the load carrying capacity of the vehicle is increased by 6 tons (from 18 tons to 24 tons), whereas the axle load of the additional axle is 9 tons (see Table 1). This 9-ton axle with single wheels causes relatively high strain peaks both in the AC layer and the subgrade (see Figure 4 and 5). Since damage to the pavement is a fourth power law function of the induced strains, this has a considerable contribution to the damage factor for the HCT truck and makes the HCT truck more damaging to the pavement compared to the 4-axle truck. It should be highlighted though that the HCT truck is less damaging to the pavement compared to the 3-axle & 2-axle trucks in most of the analyzed cases.

It should also be noted that the HCT truck has other advantages compared with the reference 2-4 axle trucks, such as increased fuel efficiency and decreased traffic congestion which should be weighed in when assessing the overall benefit of the HCT truck.

4. Conclusions

In this study the relative pavement damage risk of a 5-axle HCT truck is compared to three other reference trucks with fewer number of axles and less load carrying capacities. The analyses were carried out by simulations using the pavement analysis tool ERAPave. Three pavement structures were considered, relevant for Stockholm urban area where the HCT truck is supposed to be introduced. The analyses were conducted for two critical seasons: the spring-thaw period and the summer. The results indicate that the 4-axle reference truck is the most pavement friendly one. Generally, the HCT truck appears to be more damaging to the pavement compared to the 4-axle reference truck, but less damaging than 3-axle and 2-axle trucks. The relative damage is dependent on the pavement structure and season.

To assess the potential benefit of the HCT truck, fuel efficiency and other factors should also be weighed in, not only the pavement damage risks. For instance, if the HCT-trucks are used instead of 3-axle trucks for carrying a fixed amount of load, the number of required trips will be reduced to half, and the reduction in fuel consumption is estimated to be about 40% (Segerborg et al. 2019).

It should be noted that this is a theoretical study. There were some simplifications made during the analyses such as assuming a circular tire-pavement contact area. Only one speed of the vehicle was considered in the studies, and the material properties for only two seasons were included. The structures analyzed here were hypothetical structures which are representative of Stockholm urban area. Since the relative damage factors are related to the structure type and season, further studies should focus on the real pavement structures and scenarios. Furthermore, the damage factors were calculated based on the fourth power law function following the Asphalt Institute method, and the calculations were made using the maximum peak strain values. Further studies are needed to test the validity of this approach. Laboratory testing and full-scale testing with instrumented real pavement sections are necessary for the validation.

5. Acknowledgements

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