Impact of introducing longer and heavier vehicles on the bearing capacity of pavement subgrades

M.S. Rahman

Pavement Technology, Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden

S. Erlingsson

Faculty of Civil and Environmental Engineering, University of Iceland, Reykjavik, Iceland

ABSTRACT: Increasing the maximum permissible gross weight of vehicles from 64 tons to 74 tons on Swedish highways may significantly increase deformation in subgrades requiring extensive and expensive measures for maintenance deep down in the structures. Even though the individual axle load remains the same, longer and heavier vehicles will contain higher proportions of tandem and tridem axles and the total load will be superposed on to the subgrade resulting in higher deformations. In this study, the relative impact of single, tandem and tridem axles on subgrade deformation was analyzed based on calculations in a pavement design software called ERAPave. Three structures with different layer thicknesses and varying material properties during the spring-thaw and summer period were analyzed. In general, it was observed that the relative impact is dependent on the thicknesses and material properties of the pavement structure and the subgrade. Weaker subgrade is more affected by the tridem axle followed by tandem and single axle. The tridem axle is more damaging to the sub-grade for thicker and stiffer structures. In certain cases, the single axle showed more impact on the top of the subgrade. The tridem axle showed more vertical deflection in all cases that may induce increased fatigue cracking of the asphalt concrete (AC) layer. Duration of loading was higher for the tridem axle which has more damage potential. Thus, for the whole vehicle, containing more tridem axles, the effects may be superposed resulting in greater damage. On the other hand, the higher load carrying capacity of the tandem and tridem axle configurations will reduce the number of trips required to carry the same amount of goods. This may compensate for the increased damage to the subgrade and the impact on the life cycle of the pavement.

Keywords: Longer and heavier vehicle, subgrade, axle configuration, deformation, damage

1 INTRODUCTION

Recent trends show that longer and heavier vehicles (LHVs) benefit the economy and the environment by reducing fuel consumption and the costs of road freight transport (Ludec, 2009, Gleave et al., 2013). Historically, LHVs have been permitted to operate in Sweden. Since 1996 and as of the beginning of 2015, the maximum gross vehicle weight (GVW) of 60 tons and a length of up to 25.25 m have been permitted. In 2015, the GVW was increased to 64 tons. In 2018, the Swedish Transport Agency decided to further increase the maximum GVW to 74 tons on parts of the road network. It will probably be allowed on the entire road

network if studies and experience indicate positive impact of the LHV on traffic safety, economy and the infrastructure (Saliko and Erlingsson, 2021). Furthermore, a special permission has been granted to an iron ore producer in Northern Sweden to transport the ore using 25 m long LHVs having a gross weight of 90 tons on a road linking the mining site to the nearby train station (Erlingsson and Carlsson, 2014). Within the European Union (EU), however, the maximum permissible gross vehicle weight is 40 tons except that intermodal transports using 40-foot containers are allowed a maximum weight of 44 tons (Directive 96/53/EC) (Žnidarič, 2015).

One of the consequences of introducing 74 tons trucks in Sweden is that multiple axles (tandem and triple axles) are becoming more common. In this case, the maximum allowable load for an axle group is 24 tons. This means that the individual axle loads are reduced compared to that permitted for the drive axle (11.5 tons). As a result, stresses and strains in the upper layers of pavements are reduced. However, as the load spreads with depth, the stresses from the closely spaced axles start to superimpose and deep down in the subgrade, the total stress can exceed that permitted for the drive axle. This effect is schematically shown in Figure 1. This can be seen in field measurements as well (Saliko and Erlingsson, 2021). The consequences of this are not well-known. The conventional pavement analysis method of converting the traffic with all the different combinations of axles to the number of passes of an equivalent standard axle load (single axle with dual wheels) (ESALs) does not take this effect into consideration.

Figure 1. Schematic of stress distributions and superposition of stresses from the sub-axes of a triple-axle configuration with depth inside a typical pavement structure.

In the light of increasing the maximum GVW to 74 tons and a probable development towards even higher loads, deformations in subgrades and subbase layers have been identified as a matter of concern. Damages due to deformations in these layers can lead to very large costs in the future for maintenance and point-by-point reinforcement measures. The high costs are associated with the damages found deep down in the pavement structure requiring extensive measures. The Swedish road network largely consists of pavements that were built for completely different loads than what is experienced today. The knowledge about the detailed distribution of stresses deep in the pavement structure due to several point loads is limited, especially regarding time-dependent and non-linear responses from the asphalt concrete (AC) and unbound road materials. Indeed, several studies have been conducted to evaluate the impact of the LHVs on transport infrastructures (Leduc, 2009, Glaeser, 2006, Akerman and Jonsson, 2007, Aurell and Wadman, 2007, Knight et al., 2008, Chatti et al., 2009, Weissmann et al., 2013). In this article, the risk of damage down in the subgrade caused by the tandem and triple axles of GVW of 74 tons was assessed. This was done by calculating

the stresses and strains induced in the subgrade due to tandem and triple axles and comparing the same due to a permissible drive axle (single axle of 11.5 tons with dual tires). The study was based on the theoretical analyses of the impact of these different axle configurations on the responses of subgrade of three typical hypothetical pavement constructions during the spring-thaw and summer period.

2 METHODOLOGY

In this project, three typical pavement sections, shown in Figure 2, were studied that vary from a thin structure with 5 cm AC layer, an intermediate construction with 10 cm AC layer, to a relatively thick structure with 15 cm AC layer. Two seasons were considered critical: (a) the spring-thaw period and (b) the hot summer period. During the spring-thawing period, the AC layers are quite stiff due to the low air temperature, but the unbound layers are relatively weak since the high water-content reduces the stiffness. Stresses from the heavy axles are, therefore, well dispersed through the AC layer, but the load-spreading is relatively small in the unbound layers. This means that the risk of developing high stresses in the subgrade is high. During the summer period, the high temperature reduces the stiffness of the AC layer. On the other hand, the water-content of the unbound layers is lower for which the stiffness is higher compared to the spring-thaw period. Thus, these two seasons represent two completely opposite scenarios.

Figure 2. The three structures studied.

The calculations were conducted using the pavement analysis software ERAPave, developed at the Swedish National Road and Transport Research Institute (VTI). The program is based on multi-layer elastic theory (MLET) and considers the load to be axi-symmetrical, i.e., the contact area between the tire and the surface is circular. The impact of dual wheels and multiple axles are summed according to the theory of superposition (Ahmed, 2014).

Table 1. The three studied load cases.

Load case	Axle load [kN]	Number of sub-axles	Tire pressure [kPa]	Distance between the wheels [cm]	Distance between the axles [m]
Drive axle	115	1	800	35	-
Tandem axle	190	2	800	35	1.4
Triple axle	240	3	800	35	1.4

For the study, three load cases were considered: (a) a drive axle (single axle), (b) a tandem axle and (c) a triple axle - all with dual wheels. Table 1 provides an overview of the load cases. The speed of the vehicles was assumed to be 80 km/h.

The material parameters assumed for the summer and spring seasons are presented in Table 2 and Table 3, respectively. For each season and all structures, 2 and 3 different values of the stiffness modulus, respectively for the subbase layer and the subgrade were considered. The higher subbase modulus values represent a crushed rock material of good quality that has a low frost susceptibility and the lower modulus values correspond to an uncrushed natural aggregate of slightly lower quality. The 3 cases of subgrade materials represent a sandy soil, silty soil and a soil with high organic content. Thus, 12 structural conditions were analyzed in total. With the three load cases, the total number of scenarios is then 36.

Table 2. Selected stiffness moduli for the summer period [MPa].

	AC layer thickness [cm]		
	5	10	15
AC layer	4 000	3 000	2 500
Unbound base layer	450	450	450
Unbound subbase layer	450/240	450/240	450/240
Subgrade	50/10/5	50/10/5	50/10/5

Table 3. Selected stiffness moduli for the spring-thawing period [MPa].

	AC layer thickness [cm]		
	5	10	15
AC layer	12 000	10 000	9 000
Unbound base layer	300	300	300
Unbound subbase layer	450/100	450/100	450/100
Subgrade	50/10/5	50/10/5	50/10/5

3 RESULTS

Using ERAPave, the calculations were conducted for the three axle load configurations (Table 1) for the three structures (Figure 2) with the combinations of the material properties for spring and summer, as presented in Table 2 and Table 3. This article presents some of the typical results necessary for the discussions. All the results presented here are along the vertical longitudinal section through the middle of the dual wheels.

3.1 *Variation of stresses and strains along the depth*

In Figure 3, a typical distribution of stresses and strains along the depth of the structure (for the different layers) as induced by the different axle configurations are shown. This figure shows that the single axle produces higher stresses and strains in the upper layers which is gradually superseded by the tandem and tridem axles with depth. This study focuses on the subgrade only where it is seen that the maximum values of stresses and strains occur on the top of the subgrade which diminishes with depth.

From analyses of the results for all the scenarios, it is seen that, in some cases, the single axle may produce higher stresses and strains at the upper part of the subgrade depending on

the structure and layer properties. However, in all cases, the single axle is superseded by the tandem and tridem axles at lower depths. This situation is shown in Figure 4. In other cases, the tandem and tridem axle produce higher stresses and strains all through the subgrade layer. This situation is presented in Figure 5.

Thus, in terms of absolute maximum strain, which is induced at the top of the subgrade, the single axle may dominate in some situations. However, considering the overall strain along the depth of the subgrade, the tridem axle dominates in most of the situations which will be reflected in the total vertical deflection of the subgrade.

Figure 3. Distribution of vertical stresses and strains along the depth of structure 1 (springtime with subbase stiffness of 100 MPa and subgrade stiffness of 5 MPa).

Figure 4. Distribution of vertical stresses and strains along the depth of structure 1 (springtime with subbase stiffness of 450 MPa and subgrade stiffness of 50 MPa).

Figure 5. Distribution of vertical stresses and strains along the depth of structure 3 (summertime with subbase stiffness of 450 MPa and subgrade stiffness of 5 MPa).

3.2 Vertical deflection at the top of the subgrade

The total vertical deflection at the top of the subgrade was calculated for all cases. Here, the two typical cases as presented in section 3.1 are shown (Figure 6). It is noted that for all cases, tridem axle induces the maximum vertical deflection followed by the tandem and single axles. Thus, in this respect, the tridem axle may result in more damage to the upper AC layers due to increased fatigue cracking.

Figure 6. Total vertical deflection at the top of the subgrade: (a) structure 1, springtime with subbase stiffness of 450 MPa and subgrade stiffness of 50 MPa. (b) structure 3, summertime with subbase stiffness of 450 MPa and subgrade stiffness of 5 MPa.

3.3 Duration of loading

Vertical stresses and strains induced at two depths (one in the upper part and the other in the lower part of subgrade) with respect to time for a typical case are shown in Figure 7 and Figure 8, respectively. As can be expected, duration of loading is maximum for the tridem axle followed by the tandem and single axles. At the upper part of the subgrade (at a depth of 55.1 cm), the peaks due to the passing of each axle can be seen. This effect diminishes with depth as the load is distributed and superposed. As a result, no peaks can be seen at a depth

of 250 cm. The duration of loading is dependent on the speed of the vehicle. The longer duration of loading for the tandem axle may result in higher damage depending on the moisture and drainage condition and porosity of the subgrade. If the porosity of the subgrade is high, moisture may get expelled resulting in some settlement or permanent deformation. The longer duration may also induce more damage due to viscoelastic nature of the AC layer.

3.4 Damage ratio

The relative damage of the subgrade caused by the tandem and tridem axles compared to the single axle can be calculated based on the Asphalt Institute Method (Huang 2004). According to the permanent deformation criterion, the allowable number of load repetitions to control permanent deformation can be expressed as

$$N = a(\epsilon_v)^b \quad (1)$$

where, N is the allowable number of load cycles, ϵ_v is the vertical compressive strain at the top of the subgrade a and b (b is usually taken as -4) are material constants. A relative damage ratio (D) for a single passage can be defined as the ratio between two allowable number of load repetitions. Thus, in this study, the damage ratios for the tandem and tridem axles in relation to the single axle were computed as:

$$D = \frac{N_s}{N_t} = \left(\frac{\epsilon_{vt}}{\epsilon_{vs}} \right)^4 \quad (2)$$

Figure 7. Vertical stress with respect to time at two depths (structure 1, springtime, subbase modulus 100 MPa and subgrade modulus 5 MPa).

Figure 8. Vertical strains with respect to time at two depths (structure 1, springtime, subbase modulus 100 MPa and subgrade modulus 5 MPa).

where, N_s and N_t are the allowable number of load repetitions for the single and tandem or tridem axles, respectively. ε_{vs} and ε_{vt} are the vertical strains at the top of the subgrades for the single and tandem or tridem axles, respectively. The calculated damage ratios for all the scenarios studied here are presented in Table 4. Here, the values of D less than one (shaded grey) means that the single axle is more damaging and vice versa.

It is observed that, out of the 36 cases, single axle is more damaging in 13 cases (in one case, $D = 1$, shaded light grey), compared to the tandem axle and in 17 cases compared to the tridem axle. It can be expected that the relative damage will depend on the stiffnesses and thicknesses of the upper layers which influences the amount of load spreading and superposition. The data shows that the single axle is more damaging when the AC layer is thinner, and the base and subbase layers are weaker. The reason is that in those cases, the load spreading is relatively lower and the amount of superposition of stresses on the top of the subgrade for the multiple axles is less. Thus, the heavier weight of the single axle causes more strain on the top of the subgrade. It is again more damaging when the subgrade stiffness is higher. This implies that for similar pavement structures, the tridem axle will cause more damage to the subgrade if the subgrade is weaker. According to Table 4, D ranges from 0.27 to 3.49. The most critical situation with $D = 3.49$ (marked with box) appears to be for structure 3 loaded with the tridem axle during the springtime when the subbase and subgrade moduli are 450 MPa and 5 MPa, respectively. On the other hand, the most favorable situation with $D = 0.27$ (marked with box) occurs in structure 1 for tridem axle during the springtime with the subbase and subgrade moduli of 100 MPa and 50 MPa, respectively.

In terms of load carrying capacity, the tridem axle configuration can transport much higher load than the single axle configuration. This means that the number of trips required to transport the same amount of goods will be much fewer for the tridem axle compared to the single axle. In this respect, a much higher damage ratio (which is the ratio of the allowable number of passes) than 1 for the tridem axle can have the same impact on the life cycle of the pavement compared to the single axle.

It should be noted that the damage ratios (with respect to the single axle) were calculated at the top of the subgrade. At greater depths, D will always be the highest (and greater than 1) for the tridem axle followed by the tandem axle, as can be seen from the plots in Figure 4 and 5. Thus it may turn out that even though the tridem and tandem axles appear to be less

Table 4. Damage ratio.

		Layer stiffness [MPa]			Damage ratio (with respect to single axle)		Peak vertical strain (ϵ_{vt}) [10^{-3}]
		Base	Subbase	Subgrade	Tandem axle	Tridem axle	Single axle
Structure 1 (5 cm AC layer)	Spring	300	100	5	0.91	0.80	2.06
				10	0.72	0.53	1.64
				50	0.50	0.27	0.77
				5	1.32	1.48	0.87
				10	1.02	0.98	0.74
	Summer	450	240	50	0.61	0.40	0.46
				5	1.12	1.13	1.34
				10	0.86	0.74	1.11
				50	0.55	0.32	0.62
				5	2.12	2.52	0.71
	Spring	450	450	10	1.03	0.98	0.79
				50	0.61	0.39	0.48
				5	1.71	1.73	1.31
				10	1.31	1.12	1.02
				50	0.78	0.46	0.47
Structure 2 (10 cm AC layer)	Spring	300	100	5	2.22	2.68	0.63
				10	1.72	1.79	0.53
				50	0.98	0.69	0.33
				5	1.83	1.97	1.00
				10	1.40	1.28	0.83
	Summer	450	240	50	0.83	0.52	0.46
				5	2.12	2.52	0.71
				10	1.63	1.65	0.60
				50	0.94	0.64	0.36
				5	2.33	2.68	0.92
Structure 3 (15 cm AC layer)	Spring	300	100	10	1.75	1.75	0.72
				50	0.98	0.66	0.33
				5	2.70	3.49	0.49
				10	2.07	2.35	0.42
				50	1.12	0.86	0.25
	Summer	450	240	5	2.08	2.40	0.83
				10	1.59	1.56	0.69
				50	0.90	0.60	0.38
				5	2.36	2.95	0.60
				10	1.81	1.93	0.51
	Spring	450	450	50	1.00	0.72	0.31

harmful than the single axle for certain cases in Table 4, they can have the opposite consequences for the pavement depending on the overall structural conditions.

4 CONCLUSIONS

In this article, the impact of LHVs on the subgrades of pavement structures was theoretically analyzed. Since LHVs will consist of more tandem and tridem axles than single axles, this study focused on the relative impacts of the single, tandem and tridem axles. Three typical pavement structures were investigated here with varied material properties during the spring and the summer. The analyses were based on layered elastic theory carried out with the aid of

ERAPave which provided an overall estimate of the relative impacts of the different wheel configurations.

In general, it was observed that the relative impact is dependent on the thicknesses and material properties of the pavement structure and the subgrade. Weaker subgrade is more affected by the tridem axle followed by tandem and single axle. On the other hand, for thicker and stiffer pavement structure, the tridem axle is more damaging to the subgrade. In certain cases, the single axle showed more impact on the top of the subgrade. The tridem axle showed more vertical deflection in all cases that may induce increased fatigue cracking of the AC layer. The speed of the vehicle also has some impact on the damage. Duration of loading was higher for the tridem axle which has more damage potential. Thus, for the whole vehicle, when there are more tridem axles, the effects may be superposed resulting in greater damages. On the other hand, since tandem and tridem axle configurations have higher load carrying capacity, the number of trips required to carry the same amount of goods will be reduced compared to the single axle. This might compensate for the increased damage to the subgrade and the impact on the life cycle of the pavement.

Since this study showed that the overall impact of an LHV on a pavement structure depends on the axle configuration, structural and climatic conditions and the number of trips, it was hard to draw any generalized conclusion. The assessment should be conducted for specific cases including life cycle cost analysis. Furthermore, similar studies should be carried out for other types of structures and climatic conditions with the whole vehicle configurations. The actual damage to the subgrades and the effect on the life span of a pavement structure should as well be investigated using full scale tests or field observations. Evaluation of pavement structural responses and performance are valuable to improve the mechanistic or mechanistic-empirical pavement design and maintenance procedures under heavy traffic loading.

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