Effect of Uphill Flexible Pavements on The Damaging Effect Of Full-Trailer Trucks With Tandem Front Axles

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Abstract

The effect of traffic on flexible pavements can be expressed in terms of truck equivalence factors. This paper presents a study on the effect of uphill pavements on the damaging effect (truck equivalence factors) of two types of full-trailer trucks with tandem front axles. Axle load and geometrical characteristics survey on the two types of full-trailer trucks were carried out for determining the data needed in this study. In addition, uphill slope survey in Kerbala city was done and the data of uphill slope of other Iraqi cities were obtained from previous surveys. The paper reveals that the uphill pavement gradient causes significant increase in truck equivalence factors. In addition, the research reveals that there are many factors affecting the truck equivalence factors on uphill flexible pavements, including the total weight of full-trailer, H/B ratio (height of center of gravity to the wheel base of the truck), magnitude of uphill slope, and the structural number (SN).This work shows the importance of considering the effect of uphill slope in the design of flexible pavements on steep uphill slopes.

Keywords :- Flexible pavements; full-trailer truck; tandem front axle; truck equivalence factors; uphill slope

الخلاصة

يمكن التعبير عن تأثير حركة المرور على الأرصفة المرنة من خلال عوامل تكافؤ الشاحنات. تقدم هذه الورقة دراسة حول تأثير الارتفاعات الشاقة على التأثير المدمر (عوامل تكافؤ الشاحنة) لنوعين من شاحنات المقطورات ذات المحاور الأمامية المزدوجة. تم إجراء مسح الحمل والخصائص الهندسية لنوعين من الشاحنات القاطرة و المقطورة لتحديد البيانات المطلوبة في هذه الدراسة. وبالإضافة إلى ذلك، تم إجراء مسح المنحدر الصاعد في مدينة كربلاء، وتم الحصول على بيانات المنحدر الصاعد للمدن العراقية الأخرى من الدراسات الاستقصائية السابقة. ويكشف البحث أن الرصيف الصاعد يسبب زيادة كبيرة في عوامل تكافؤ الشاحنات. وبالإضافة إلى ذلك، يكشف البحث أن هناك عوامل كثيرة تؤثر على عوامل تكافؤ الشاحنة على الأرصفة المرنة الشاقة، بما في ذلك الوزن الإجمالي للمقطورة الكاملة، نسبةH/B (ارتفاع مركز الثقل إلى قاعدة العجلات للشاحنة)، قيمة المنحدر الصاعد، والعدد الهيكلي (SN). ويبين هذا العمل أهمية النظر في تأثير المنحدر الصاعد في تصميم التبليط المرن على المنحدرات الشاقة شديدة الانحدار.

الكلمات المفتاحية :-أرصفة مرنة، شاحنة مقطورة كاملة، محور امامي مزدوج ،عوامل تكافؤ الشاحنات، المنحدر الصاعد

1. Introduction

Transportation is a part of a production. With growth of industrial and agricultural production, all the transport volume is growing as well leading to increase traffic volume, especially of commercial vehicles (trucks) as well as their axle loads. This resulted into serious deteriorations that started to appear in road pavements. Overloading is among the most important causes of the deterioration of flexible pavements. This is especially critical in developing countries where the transportation of heavy freight on city roads and highways is increasing (Chan, 2008; Fekpe and Oduro-Konadu, 1993; Maheri and Akbari, 1993; Pearson-Kirk,1989). The pavement damage caused by any type of vehicle (axle) is usually identified by the equivalent axle load factor or load equivalency factor (Green and Morse, 1994; Lee and Garner, 1996). In fact, the land topography is not quite flat and there is a vertical alignment of a highway on rolling and mountainous topography consisting of tangents connected by vertical crest and/ or sag curves. The damaging effect (equivalency factor) of vehicles moving on pavements is different on an uphill slope than on level highways. The uphill slope causes a redistribution of axle loads (Razouki and Mohee, 1999). It is worth mentioning that Razouki and Radeef (2005) pointed out that the destructive effect of single unit trucks on uphill slopes of flexible pavement is greater than on a level pavement. However, the increase of damage to rigid uphill pavements of highways and ramps of interchanges with predominating full-trailer traffic with single front axles has received consideration by Razouki and Al-Muhanna (2010). They pointed out that this fact is of great importance, especially in developing countries with common phenomenon of overloading. Razouki and Al-Muhanna (2010) showed that the increase in pavement slab thickness due to increased truck equivalence factors on uphill rigid pavement increases with increasing uphill slope magnitude.

2. Classification of Full-Trailer Trucks

The full-trailer truck is a trailer that is pulled by a drawbar (hook) attached to the preceding tractor unit, but the drawbar transfers no weight to the preceding unit (Harwood, 2003). The full-trailer trucks were classified into different types depending on the axle configuration. Jones and Robinson (1976) developed a code used to represent axle configuration of commercial vehicles. Each axle is represented by a digit, usually'1' or '2' depending on how many wheels are on each end of the axle. Tandem axles are indicated by recording the digits directly after each other and a decimal point is placed between the code for a vehicle's front and rear axles. The code for trailers is recorded in the same way as for single-unit trucks and is separated from the tractor unit code by a 'plus' sign.

3. Axle Load Survey

To determine the truck equivalence factors, an axle load survey is required. This survey was carried out to determine the axle load distribution of the full-trailer truck on level pavements. The axle load survey will also provide important information about the degree of overloading. There are three main ways of measuring axle loads using either a fixed weighbridge (permanent weighbridge), portable weigh pads, or weigh-in-motion equipment (Rys *et.al.,*2016; TRL Limited, 2004). The weighing procedure depends on the type of weighing system. For a permanent weighing system, the weighing procedure was planned to get each axle load individually. However, Kerbala silo and Hilla silo were selected for this purpose. This survey covered 89 full-trailer trucks type 11.2+ 2.2 and 11.22+ 2.22. The procedure for weighing the full-trailers to get axle load individually was as follows:

The full-trailer truck must be driven onto the platform and must be stopped and weighed as each axle in turn mounts the platform. In this way the weight of each axle can be calculated by difference (see Fig. 1) (TRL Limited, 2004).

Table 1 shows typical axle load results obtained from the survey for full-trailer trucks type 11.2+2.2 and 11.22+2.22.

4. Geometrical Characteristics of Full-Trailer Trucks

The geometrical characteristics of full-trailer trucks have an important effect on the damaging effect of full-trailer trucks on uphill pavements (Razouki and Al-Muhanna, 2010; Razouki and Radeef, 2005).

Fig. 1: Axle load survey of (11.22+2.22) trucks in Kerbala silo permanent weighing station.

Table 1: Typical axle load results obtained from the survey for full-trailer trucks type 11.2+2.2 and 11.22+2.22.

Full-trailer truck type	L= loaded E= empty	Tractor unit			Trailer unit			W_t (Tonne)
		F_1 (Tonne)	R_1 (Tonne)	W_1 (Tonne)	F_2 (Tonne)	R_2 (Tonne)	W_2 (Tonne)	
11.2+2.2	E	9.88	5.68	15.56	5.41	6.44	11.85	27.41
11.2+2.2	L	18.46	25.70	44.16	14.07	23.71	37.77	81.93
11.22+2.22	E	9.48	8.34	17.82	5.23	7.89	13.12	30.94
11.22+2.22	L	19.09	33.43	47.43	12.41	23.97	36.38	83.80
11.2+2.2	L	16.72	21.64	38.36	11.43	17.62	29.05	67.41
11.22+2.22	L	14.49	23.05	34.03	9.988	15.25	25.24	59.27

The geometrical characteristics of full-trailer trucks such as the length of wheel base (B), height of center of gravity (H) of truck above the pavement, the axle geometry and the height of the drawbar (E) (between the tractor unit and the trailer) above the pavement are shown in Fig. 2.

The center of gravity for a truck depends on many factors such as type of truck, type of loading, and degree of loading. It also differs from one truck model to another. The determination of the center of gravity is a very difficult task (Razouki and Al-Muhanna, 2010). For this reason, the heights h_1 and h_2 for the tractor and h_3 and h_4 for the trailer units (see Fig. 2) were measured. These heights will help in estimating the height of center of gravity for each unit of the full-trailer truck. These two geometrical characters allowed an estimate for the lower and upper bounds of the H/B ratio for the tractor and trailer units as the H/B ratio is needed to arrive at the axle loads on uphill pavement. This study revealed that the H/B ratio fluctuates between 0.2 and 1.0 and it is assumed that this ratio is the same for the tractor and the trailer units.

The elevation of the drawbar (between the tractor unit and the trailer) above the pavement was about 100 cm.

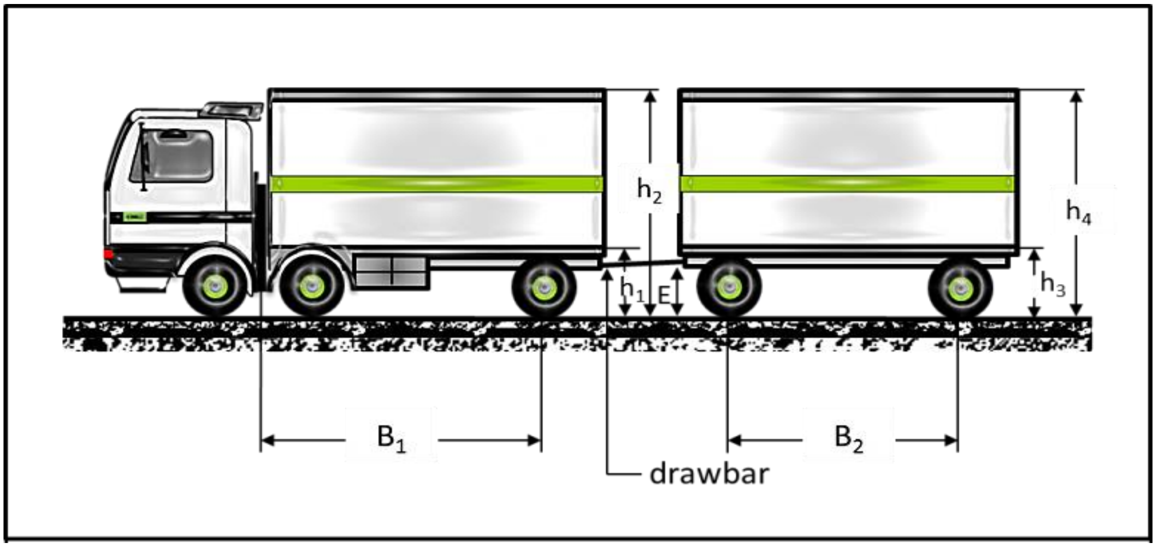

Fig. 2: Vehicle dimensions for (11.2+2.2) full –trailer trucks.

Table 2 shows typical geometrical characteristics results obtained from the survey of this study for full-trailer truck type (11.2+2.2 and 11.22+2.22).

Table 2: Typical results of the geometric characteristics for full-trailer truck type (11.2+2.2) and (11.22+2.22).

Type of full-trailer truck	Tractor unit			Trailer unit		
	B_1 (mm)	h_1 (mm)	h_2 (mm)	B_2 (mm)	h_3 (mm)	h_4 (mm)
11.2+2.2	4710	1276	2870	5440	1256	3200
11.2+2.2	4875	1298	3200	5590	1539	3300
11.2+2.2	3163	1345	2890	3880	1600	3020
11.22+2.22	4220	1300	3200	4950	1490	3480
11.22+2.22	3738	1460	3700	3990	1400	3690
11.22+2.22	5200	1300	2734	4200	1600	2890

5. Pull Force Between The Tractor And The Trailer Units of Full-Trailer Trucks

To arrive at a formula that relates the pull force in the drawbar between tractor and trailer units, Al-Muhanna (2008) carried out a survey on (66) full-trailers of different types and with different degree of loadings. The instruments used in Al-Muhanna (2008) survey consisted of the digital portable strain meter, strain gauges, and a connecting element between the tractor and the trailer. The 66 pull force data obtained by Al-Muhanna (2008) has been correlated by him, with the corresponding weights of the trailer units. The following non-linear regression (see equation 1) was adopted throughout this work with a correlation coefficient of (0.93).

$$T_o = 0.0008 \times (W_2)^{\wedge 1.5433} \tag{1}$$

Where W_2 is the total weight of the trailer unit in kN and T_o is the pull force for the case of level highway in kN. Note that equation 1 is applicable for trailer units with a total weight between 73.379 and 462.443 kN.

6. Uphill Slope Survey

To determine the maximum uphill slope of existing highways and interchanges in Iraq, an uphill slope survey was carried out during this work on Kerbala roads and interchanges to add it to the survey carried out by Al-Muhanna (2008) in some governorates in Iraq such as Sulaimaniya, Erbil and Dohouk. The maximum uphill slope for ramps of interchanges in Kerbala city was 7%. However, Razouki and Al-Muhanna (2010) reported that the measured maximum grade for some mountainous highways in north of Iraq (Dohouk, Sulaimaniya and Erbil) was 18%. For the purpose of this work, the range of uphill slope considered in this work to represent uphill slopes in Iraq was from 0 to 18%.

7. Axle Loads on Uphill Pavements

On uphill pavements, there is a redistribution of axle loads of any truck caused by the moment produced by the component of the weight of truck parallel to the road surface. As a result, the damaging effect of axle loads of a full-trailer truck (expressed in terms of the AASHTO load equivalency factors) on uphill pavements is largely different from that on a level pavement.

On uphill slope, the pull force (T) between the tractor and the trailer unit becomes related to the vertical component as well as the component of the weight of the trailer unit parallel to the road surface (see Fig. 3). It should be noted that it was not possible to measure the pull force for the case of uniform motion of full-trailer on uphill slope (Al-Muhanna, 2008).The same equation of the pull force on level roads will be taken on the uphill slope but after multiplying the weight (W_2) by ($\cos\theta$) and adding to this equation the component of the weight of the trailer unit parallel to the uphill pavement as follows:

$$\mathbf{T = 0.0008 \times (W_2 \times \cos\theta)^{1.5433} + W_2 \times \sin\theta} \tag{2}$$

where Θ denotes the angle of uphill slope. When applying Θ = 0 to Eq. (1), T returns to T_o (the case of a level road).

The application of the equations of equilibrium for each of the tractor and the trailer units yields (see Fig. 3).

$$F_{G1} = F_1 \times \cos\theta - W_1 \times \sin\theta \times H_1/B_1 - T \times E/B_1 \tag{3}$$

$$R_{G1} = R_1 \times \cos\theta + W_1 \times \sin\theta \times H_1/B_1 + T \times E/B_1 \tag{4}$$

$$F_{G2} = F_2 \times \cos\theta - W_2 \times \sin\theta \times H_2/B_2 + T \times E/B_2 \tag{5}$$

$$R_{G2} = R_2 \times \cos\theta + W_2 \times \sin\theta \times H_2/B_2 - T \times E/B_2 \tag{6}$$

Where F_1 and R_1 are the front and rear axle loads for tractor unit on level pavement respectively, F_2 and R_2 are the front and rear axle loads for trailer unit on level pavement respectively, F_{G1} and R_{G1} are the front and rear axle loads for tractor unit on uphill slope respectively, F_{G2} and R_{G2} are the front and rear axle loads for trailer unit on uphill slope respectively, W_1 and $W_2$are the total weight of the tractor and trailer units respectively, B_1 and B_2 are the wheel base lengths for the tractor and trailer units respectively, H_1 and H_2 are the heights (above and perpendicular to the pavement) of the center of gravity for the tractor and the trailer units respectively, E is the height of the pull force above the pavement, Θ = angle of slope, tan (Θ) =grade.

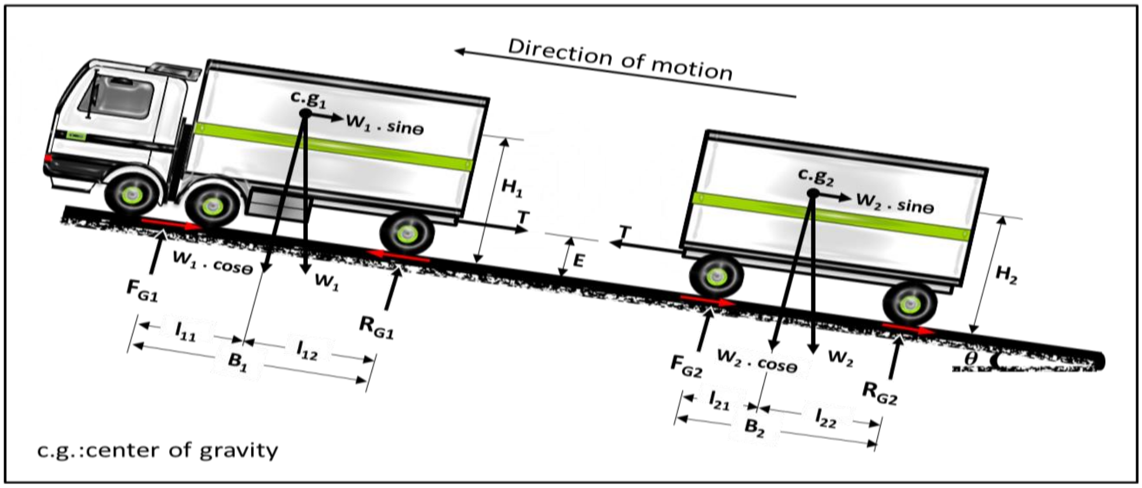

Fig. 3: Axle loads of full-trailer moving on an uphill pavement with a uniform motion.

8. Effect Of Uphill Pavement On Truck Equivalence Factors Of Full-Trailer Trucks

The truck equivalence factor (TEF) is the summation of load equivalency factors for the front and rear axle loads of a particular vehicle (AASHTO-Guide, 1993). It is used to express the effect of axle loadings on the design of flexible highway pavement. The average truck equivalence factor (Ta) can be calculated as follows:

$$T_a = \frac{\sum_{j=1}^{n} \left(T_{ej} \right)}{n} \tag{7}$$

Where T_{ej} is the truck equivalence factor for jth truck (jth full-trailer), n is the total number of full trailers.

Tables 3 and 4 present the average truck equivalence factors on an uphill slope of full-trailer truck type 11.2+2.2, and 11.22+2.22 respectively for a terminal level of serviceability (p_t) of 2.5.

Table 3: Average truck equivalence factors for full- trailer trucks of type 11.2+2.2for p_t=2.5.

H/B	Uphill slope (%)	Structural Number, SN					
		1	2	3	4	5	6
0.2	0	141.8140	129.4620	102.2280	79.1531	71.3588	74.5225
	6	159.5570	145.5460	114.6030	88.1754	78.7908	81.6368
	12	177.1570	161.4940	126.8590	97.0823	86.0816	88.5392
	18	193.9610	176.7190	138.5430	105.5490	92.9725	94.9959
0.4	0	141.8140	129.4620	102.2280	79.1531	71.3588	74.5225
	6	174.0300	158.6650	124.6990	95.5372	84.8570	87.4591
	12	210.1790	191.4280	149.8880	113.8700	99.8943	101.7196
	18	249.2600	226.8430	177.1000	133.6510	116.0690	116.9295
0.6	0	141.8140	129.4620	102.2280	79.1531	71.3588	74.5225
	6	189.7610	172.9260	135.6700	103.5360	91.4434	93.7634
	12	248.7290	226.3710	176.7650	133.4560	115.9870	116.9994
	18	317.9760	289.1240	224.9970	168.5450	144.6900	143.9238
0.8	0	141.8140	129.4620	102.2280	79.1531	71.3588	74.5225
	6	206.8100	188.3800	147.5590	112.2020	98.5738	100.5702
	12	293.3270	266.7930	207.8530	156.1030	134.5720	134.5612
	18	401.9930	365.2690	283.5470	211.1860	179.5990	176.6379
1	0	141.8140	129.4620	102.2280	79.1531	71.3588	74.5225
	6	225.2370	205.0830	160.4080	121.5660	106.2740	107.9013
	12	344.5340	313.2040	243.5410	182.0980	155.8780	154.6019
	18	503.4150	457.1830	354.2130	262.6370	221.6430	215.8033

Table 4: Average truck equivalence factors for full- trailer trucks of type 11.22+2.22 for p_t=2.5.

H/B	Uphill slope (%)	Structural Number, SN					
		1	2	3	4	5	6
0.2	0	17.2569	16.2546	14.1226	12.6726	12.8465	13.8682
	6	18.6521	17.5190	15.0933	13.3877	13.4932	14.6012
	12	20.0035	18.7408	16.0213	14.0561	14.0860	15.2719
	18	21.2493	19.8638	16.8643	14.6496	14.6026	15.8552
0.4	0	17.2569	16.2546	14.1226	12.6726	12.8465	13.8682
	6	19.3900	18.1866	15.6021	13.7536	13.8103	14.9532
	12	21.9517	20.5047	17.3705	15.0402	14.9511	16.2245
	18	24.8282	23.1056	19.3502	16.4804	16.2229	17.6252
0.6	0	17.2569	16.2546	14.1226	12.6726	12.8465	13.8682
	6	20.2859	18.9976	16.2217	14.2036	14.2054	15.3917
	12	24.5352	22.8451	19.1660	16.3640	16.1285	17.5169
	18	29.8370	27.6450	22.8423	19.0790	18.5413	20.1400
0.8	0	17.2569	16.2546	14.1226	12.6726	12.8465	13.8682
	6	21.3390	19.9514	16.9518	14.7375	14.6782	15.9158
	12	27.7569	25.7648	21.4103	18.0308	17.6197	19.1449
	18	36.3123	33.5152	27.3688	22.4683	21.5693	23.3918
1	0	17.2569	16.2546	14.1226	12.6726	12.8465	13.8682
	6	22.5492	21.0476	17.7921	15.3554	15.2289	16.5251
	12	31.6269	29.2728	24.1112	20.0474	19.4278	21.1056
	18	44.3243	40.7801	32.9823	26.6868	25.3267	27.3793

It is quite obvious from these tables that the T_a is affected by many factors such as structural number (SN), magnitude of uphill gradient, H/B ratio and the number of tires (contact area) touching the pavement surface. The T_a decreases generally with increasing structural number. Also, these tables reveal that the T_a increases with increasing the magnitude of uphill gradient. This effect is clearly pronounced in full-trailer trucks type 11.2+2.2. However, this effect is of little significance for full-trailer trucks type 11.22+2.22. On the other hand, it is quite obvious that T_a increases most rapidly with increasing H/B ratio for full-trailer type 11.2+2.2, while for full-trailer truck type 11.22+2.22 the increase is of less significance. Also, the number of tires has a great effect on T_a. Increasing the contact area will lead to decrease the average truck equivalency factor T_a .

9. Conclusions

Based on the findings from the study, the main conclusions can be summarized as follows:

1. The average truck equivalency factor of full-trailer trucks type 11.2+2.2 and 11.22+2.22 on uphill flexible pavements is greater than on level pavements for all values of SN.
2. The average truck equivalency factor increases with increasing magnitude of uphill slope for the two types of full-trailer trucks.
3. On uphill slope, the average truck equivalency factor generally decreases with increasing structural number.
4. The average truck equivalency factor of the full-trailer truck type 11.2+2.2 is higher than that of the 11.22+2.22 full-trailer truck for the same condition of total weight of the truck, structural number, uphill slope, H/B ratio and terminal level of serviceability. This is mainly due to increasing the number of axles (tires) for 11.22+2.22 full-trailer truck which means that the contact area increased.

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