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Civil Engineering

Effect of Including the Empty-adjusted Truck Factors on Pavement Design: A Case Study on Riyadh Area Road Network

Essam A. Sharaf and Abdullah I. Al-Mansour
Department of Civil Engineering, College of Engineering
King Saud University, P.O.Box 800, Riyadh 11421

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Abstract. Truck traffic is one of the major inputs to any pavement design procedure. In almost all pavement design procedures, truck traffic is represented in terms of the accumulated Equivalent Axle Load (EAL) applications. The level of EAL applications is mainly dependent on the prevailing values of truck factors. Thus efforts have to be made to accurately estimate truck factor values based on local loading conditions. The current practice of the Ministry of Communications (MOC) involves recording axle weights of loaded trucks only without including empty trucks. This, in turn, leads to higher truck factor estimates and consequently over-designed pavement structures. The main objective of this study is to quantify the effect of excluding empty trucks when estimating truck factors, on highway pavement design. The truck factors associated with loaded trucks were determined from MOC data files. The empty truck factors were determined from a field sample consisting of 4000 empty trucks. The empty-adjusted truck factors were calculated as the weighted average of the two truck factor values. An analysis has been conducted to study the effects of using the empty-adjusted truck factors on pavement design instead of loaded truck factors, using the AASHTO design procedure. The analysis indicated that the average truck factor for empty trucks is about 1.15, the average truck factor for loaded trucks is about 9.87 and the average empty-adjusted truck factor is about 6.63. It also showed that excluding empty trucks would result in over-designs with an average of about SR 1.0 / m^2 or about SR 3500 / km-lane extra construction cost.

Introduction

General

Highway traffic is typically a combination of many different types of vehicles having different gross weights and configuration. However, most pavement design procedures require that these applied loads be converted into an equivalent number of applications of a standard axle load. The 18-kip Single Axle Load (18-kip ESAL) is the standard axle load used most widely by highway agencies. The process of collecting mixed traffic data and converting it to 18-kip ESAL's is complex. Detailed traffic data must be gathered and analyzed to identify the types of vehicles using the facility and to estimate their volumes and weights. Past, current and potential traffic growth trends must be recognized to allow proper estimates of past traffic loads and reliable prediction of future loads. These load applications can then be converted to an equivalent number of applications of a standard design axle load using "equivalent damage" concepts.

One principle of pavement design specifies that different wheel loads and load configurations produce different stresses and strains in the various layers of a pavement structure[1]. Larger and more concentrated loads produce larger stresses and strains, with thicker layers carrying higher flexural stresses than thinner layers. The repeated application of these stresses and strains causes load-related pavement deterioration. The rate of pavement deterioration varies directly with the magnitude of the repeated stresses and strains.

The AASHTO Road Test data [2] were used to develop equations predicting the number or axle applications , of a given magnitude and configuration, required to cause a given loss of serviceability. These complex equations were also used to develop Load Equivalency Factor (LEF) for various pavement types, pavement strengths and serviceability values. Each (LEF) is computed as the ratio between number of 18-kip single load applications to cause a given loss of serviceability to the number of X-kip single or (tandem) axle load applications to cause the same loss of serviceability.

Equivalency factors

The relative damage caused by different axle weights and configurations are assessed by calculating the Equivalency Factors (EF), which is defined as the relative damage caused by a particular axle with respect to the damage caused by a standard axle.

There are several methods to calculate the Equivalency Factors (EF) associated with different axle loads and configurations. The most common two methods, however, are:

1) Empirical approach based on the AASHTO road test results [2]
2) Mechanistic-empirical approach [3].

Equivalency factors based on the AASHTO road test results

The EF is given by the following equation

$$EF = \frac{W_{t18}}{W_{tx}}$$

where,

EF = Equivalency Factor

W_{tx} = the number of x-axle load applications at the end of time t

W_{t18} = the number of 18 kip single axle load applications to time t

The ratio $EF = \frac{W_{t18}}{W_{tx}}$ can be determined by solving the original AASHTO equation given below

$$\log\left(\frac{W_{tx}}{W_{t18}}\right) = 4.79\log(18+1) - 4.79\log(L_x + L_2) + 4.33\log(L_2) + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}}$$

where,

$$G_t = \log\left(\frac{4.2 - p_t}{4.2 - 1.5}\right)$$

$$\beta_x = 0.40 + \frac{0.081(L_x + L_2)^{3.23}}{(SN+1)^{5.19}\,L_2^{3.23}}$$

L_x = the load in kip on one single axle, one set of tandem axles, or one set of tridem axles

L_2 = the axle code, 1 for single axle, 2 for tandem axles and 3 for tridem axles

SN = Structural Number, which is a function of the thickness and modulus of each layer and the drainage conditions of base and subbase

p_t = terminal serviceability, which indicates the pavement condition to be considered as failure

G_t = is function of p_t as shown in the above relation

β_{18} = is the value of β_x when L_x is equal to 18 and L_2 is equal to 1

Equivalency factors based on mechanistic-empirical approach

In this approach, the EF is determined based on a prescribed failure criterion. A common and widely used failure criterion is the fatigue cracking.

The failure criterion for fatigue cracking is expressed as:

$$N_f = f_1\,(\varepsilon_t)^{-f_2}\,(E_t)^{-f_3}$$

where,

N_f = the allowable number of repetitions tp prevent fatigue cracking
ε_t – the tensile strain at the bottom of asphalt layer
E_1 = the elastic modulus of asphalt layer
f_1, f_2 and f_3= constants determined from laboratory fatigue tests with f_1 modified to correlate with field performance observations

EF is defined as: $$\left(\frac{\varepsilon_X}{\varepsilon_{18}}\right)^{f_2}$$

where,

ε_x = the tensile strain at the bottom of asphalt layer due to an x-axle load
ε_{18} = the tensile strain at the bottom of asphalt layer due to an 18-kip axle load.

It is reasonable to assume that the tensile strains are directly proportional to axle loads [4]. Thus,

$$EF = \left(\frac{L_X}{L_s}\right)^{f_2}$$

where,

L_s is the load on standard axles which have the same number of axles as Lx.

The study reported in Reference [4] proved that f_2 can be assumed equal to 4. This way, the Equivalency Factor can be determined using the following simplified formula

$$EF = \left(\frac{L_x}{L_s}\right)^4$$

The L_s values depend on axle configuration. The recommended Ls values are given below [5]:

Axle type	L_s (ton)
Single axle with single tires	5.4
Single axle with dual tires	8.2
Dual axle with tandem tires	13.6

Similar analysis was conducted using another failure criterion, namely the permanent deformation (8). This analysis produced results similar to those obtained under the fatigue cracking failure criterion.

Once the equivalency factors associated with different axle configurations are determined, the Truck Factor values associated with any truck type can be calculated as follows:

$$TF = \sum_{i=1}^{n} EF_i$$

where,

- TF = Truck Factor value associated with a specific truck type, which indicates the relative damage resulting from one pass of a specific truck on the pavement structure
- EF_i = Equivalency Factor value of the ith axle group.
- n = Number of axle group in the truck type under consideration.

Study Objectives

The main objectives of this study can be summarized in the following:

i. Estimate the overall truck factor values associated with trucks using the Riyadh area road network taking into consideration empty trucks (empty-adjusted truck factors).

ii. Investigate the effect of the empty-adjusted truck factor values on pavement design.

Data Collection

To accurately estimate the value of truck factors associated with trucks using highway network, both loaded and empty trucks have to be included. Since the Ministry of Communications (MOC) truck weight files include only loaded trucks, it was decided to conduct a field experiment to identify the percent of empty truck of each truck type. A sample of about 4000 trucks was collected from three weigh stations: Riyadh-Taif, Riyadh-Damam and Riyadh-Qassim. The data included truck type, axle weight and truck load types (including empty trucks).

On the other hand, the MOC data files were obtained for the same period from the same three stations. The data covered information of about 15000 trucks. These files included the axle weight data for the loaded trucks, truck type and truck load types. It should be noted that the data collection was restricted to truck types 1, 2, 4 and 6, according to MOC identification, because these truck types constitute more than 97% of the total number of trucks and also they produce more than 95% of the total Equivalent Single Axle Load (ESAL) applications [6,7]. Table 1 includes the axle configuration of those truck classes.

Table 1. Axle configuration of MOC truck classes included in the analysis

Truck class	First axle	Second axle	Third axle
1	Single axle single tires	Single axle dual tires	---
2	Single axle single tires	Tandem axle	---
4	Single axle single tires	Single axle dual tires	Tandem axle
6	Single axle single tires	Tandem axle	Tandem axle

Data Analysis and Results

General statistics

Table 2 shows the total number of loaded trucks, as obtained from MOC files, and the corresponding percentage; the total number of trucks surveyed, the number of empty trucks and corresponding percentage for each truck class. The overall percentage of the empty trucks from the field data was found to be about 38%.

Table 2. Number of truck types included in the study

Truck class	No. of trucks (MOC) Files	% of all trucks (MOC) Files	No. of trucks (field data)	No. of empty trucks (field data)	% of empty trucks (field data)
1	1314	8.9	294	127	43
2	793	5.3	117	31	26
4	11498	77.8	3309	1239	37
6	1175	8.0	252	110	44
Total	14780	100	3972	1507	38

Calculation of truck factors

The fourth power relation of the general equation, presented in the introduction, was used to calculate the truck factors. This has required the calculation of the equivalency factor associated with each axle group within each truck class. The average axle weight for empty trucks, obtained from the field data, were used to calculate the axle equivalency factors and the empty truck factors. Truck factors of the loaded trucks were calculated using the data from MOC files.

Table 3 summarizes the average truck factor values for empty trucks, loaded trucks and the overall values for each of the truck classes.

Table 3 shows that the average truck factors for empty trucks is 1.15, the average truck factor for loaded trucks is about 9.87 and the average empty-adjusted truck factor is about 6.63. This means that there is a reduction in truck factors of about 33% as a result of including empty trucks.

Effect of considering empty-adjusted truck factors on pavement design

The Equivalent Single Axle Load (ESAL) applications is the most widely used traffic representation in pavement design. In the AASHTO flexible pavement design equation

Table 3. Truck factor results

Truck class	Axle group	Average truck factor		Overall average
		Empty	Loaded	
	1	0.802	1.69	1.3
1	2	0.245	3.4	2.01
	3	—	—	—
	Total	1.047	5.09	3.11
	1	0.449	5.23	4.01
2	2	0.07	2.56	1.92
	3			—
	Total	0.519	7.79	5.93
	1	0.796	1.70	1.36
4	2	0.312	5.50	3.57
	3	0.087	3.83	2.44
	Total	1.195	11.03	7.37
	1	1.0	1.09	1.05
6	2	0.128	1.42	0.86
	3	0.17	2.79	1.65
	Total	1.298	5.30	3.56
All trucks		1.154	9.872	6.629

[8], the value of the accumulated ESAL is estimated and the equation is solved for Structural Number (SN) knowing the other parameters. The equation is as follows:

$$\log_{10}\left(\sum ESAL\right) = Z_i * S_o + 9.36 * \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\dfrac{APSI}{4.2-1.5}\right]}{0.40 + \dfrac{1094}{(SN+1)^{5.19}}}$$

Where:

ΣSAL = accumulated Equivalent Single Axle Load applications during the design life
Z_R = standard normal distribution variable value at reliability level (R)
S_O = overall standard deviation
SN = pavement Structural Number
ΔPSI = drop in serviceability

The value of the ((ESAL) can be calculated using the following equation:

$$(\Sigma ESAL) = 365 * P_t * AADT * GF * TF$$

Where

P_t = Percent of trucks

AADT = Current Average Annual Daily Traffic

GF = Growth factor for trucks

TF = Average truck factor

A key value in the above equation is the average Truck Factor (TF). Since the TF values obtained from MOC data files represents the loaded trucks, then the estimated (ESAL values would be higher and would produce an over-designed pavement structure. From Table 3, the average loaded truck factor for all trucks is 9.872, and the average empty adjusted truck factor is 6.629. Thus, referring to the above equation,

$$\frac{\sum \text{ESAL for empty} - \text{adjusted condition}}{\sum \text{ESAL for loaded condition}} = \frac{6.629}{9.872} = 0.67$$

Which indicate that the design should be based on (EAL value equals to 0.67 of that estimated using MOC loaded truck factor values. To assess this effect, the AASHTO design equation was used and SN values were determined under the following two conditions:

1. Using the MOC (loaded) Truck factors
2. Using the empty-adjusted Truck factors

The following values were used in the analysis

* ΣESAL = 10^6, $5*10^6$, and $20*10^6$
* Mr = 5000, 15000, and 40000 psi
* ΔPSI = 4.2 - 2.5 = 1.7
* S_o = 0.35

Table 4 includes a summary of the results of this analysis. For each case the SN using the loaded truck factors as well as the SN using the empty adjusted truck factors were calculated. The ratio of the two SN values was also recorded. Finally the difference between the two SN values was converted to an equivalent thickness of Asphalt Concrete course (AC), granular Base Course (BC) and granular Subbase Course (SB) using layer coefficients of 0.44 for AC, 0.14 for BC and 0.11 for SB, as recommended by AASHTO design procedure. The following formula was used to calculate the equivalent thickness:

$$\text{Equivalent Thickness} = \frac{SN_{(\text{loaded})} - SN_{(\text{empty-adjusted})}}{\text{Layer Coefficient}}$$

The results as presented in Table 4, indicate that using truck factors obtained directly

Table 4. Effect of including empty trucks in truck factors calculation on pavement design

(EAL (Loaded)	(EAL (Empty-adjusted)	MR	PSI (psi)	So	Structural number (SN) Loaded	Empty	Ratio	Thickness equivalent (cm) AC[1]	BC[2]	SH[3]
		5000			4.04	3.80	0.94	1.39	4.34	5.54
10^6	$0.67 * 10^6$	15000	1.7	0.35	2.70	2.50	0.93	1.14	3.63	4.62
		40000			1.82	1.70	0.93	0.69	2.18	2.77
		5000			5.14	4.85	0.94	1.68	5.26	6.71
$5 * 10^6$	$3.35 * 10^6$	15000	1.7	0.35	3.50	3.26	0.93	1.39	4.34	5.54
		40000			2.40	2.23	0.93	0.99	3.07	3.94
		5000			6.20	5.88	0.95	1.85	5.82	7.39
$20 * 10^6$	$13.4 * 10^6$	15000	1.7	0.35	4.33	4.10	0.95	1.32	4.17	5.31
		40000			2.81	2.81	0.94	1.09	3.45	4.39

1. AC = Asphalt Concrete Equivalence Thickness, based on layer coefficient $a_1 = 0.44$

2. BC = Granular Base Course Equivalence Thickness, based on layer coefficient $a_2 = 0.14$

3. SB = Granular Subbase Course Equivalence Thickness, based on layer coefficient $a_3 = 0.11$

from MOC data files (loaded) will produce pavement structures that are over-designed by about 5 to 7 %. This corresponds to about 0.76 to 1.78 cm of asphalt concrete surface, 2.29 to 5.84 cm of granular base course and 2.54 to 6.61 cm of granular subbase course

The above analysis was further extended to determine the additional costs resulting from excluding empty trucks. This was done by converting the additional layer thicknesses shown in Table 4 to the corresponding unit costs. The unit costs associated with different layers were obtained from several recent contracts obtained from the Ministry of Communications [9]. The following simple unit cost estimation equations were obtained:

$$\text{Asphalt Concrete (AC) cost (SR/m}^2) = 5 + (H_{AC} - 3)$$
[based on a minimum thickness of 3 cm]

$$\text{Granular Base Course (BC) cost (SR/m}^2) = 0.1 * H_{BC}$$
[based on a minimum thickness of 15 cm]

$$\text{Granular Subbase Course (SB) cost (SR/m}^2) = 0.067 * H_{SB}$$
[based on a minimum thickness of 15 cm]

This way, the additional costs resulting from excluding empty trucks can be calculated as follows:

$$\Delta C_{AC} = \Delta H_{AC}$$
$$\Delta C_{BC} = 0.1 * \Delta H_{BC}$$
$$\Delta C_{SB} = 0.067 * \Delta H_{SB}$$

Where,

ΔC_{AC}, ΔC_{BC}, and ΔC_{SB} = additional costs associated with the asphalt concrete, base course and subbase course, respectively (SR/m^2)

ΔH_{AC}, ΔH_{BC}, and ΔH_{SB} = additional thicknesses associated with the asphalt concrete, base course and subbase course, respectively (cm)

The additional thicknesses shown in Table 4 were used along with the above equations to determine the additional costs associated with different layers under different loading and subgrade strength conditions. The following figure summarizes those results.

The results shown in the figure indicate that the additional costs range from about 1.9 to 0.7 SR/m^2 for the Asphalt Concrete, from about 0.60 to 0.25 SR/m^2 for the Base Course, and from about 0.50 to 0.20 SR/m^2 for the subbase. For simplicity, an average additional cost of 1.0 SR/m^2 was considered to conduct the following hypothetical analysis to estimate the additional pavement design costs resulting from excluding empty trucks in the EAL applications estimation:

Average additional cost = 1.0 SR/m^2

Average additional cost per lane-km (3500 SR assuming that the Riyadh area road network (about 24,000 lane-km) was designed on the basis of loaded truck factors, then

Average additional cost for the Riyadh area = 3500 * 24,000 (84,000,000 SR)

Conclusion

Based on the results obtained from the sample considered in this study, the following may be concluded:

1. Based on the 4000 trucks field sample, it was found that the average percent empty trucks is about 38%.

2. The average truck factor for empty trucks is about 1.15, the average truck factor for loaded trucks is about 9.87 and the average empty-adjusted truck factor is about 6.63.

3. The effect of using loaded truck factors without considering empty trucks can lead to an over-design ranging from 5 to 7%. This is equivalent to about 0.76 to 1.78 cm of asphalt concrete, or 2.29 to 5.84 cm of granular base course, or 2.54 to 6.61 cm of granular subbase.
4. The corresponding additional costs were estimated to be about 1.9 to 0.7 SR/m^2 for the asphalt layer, 0.6 to 0.25 SR/m^2 for the granular base course and 0.5 to 0.2 SR/m^2 for the granular subbase. Thus, under the assumption that the Riyadh area

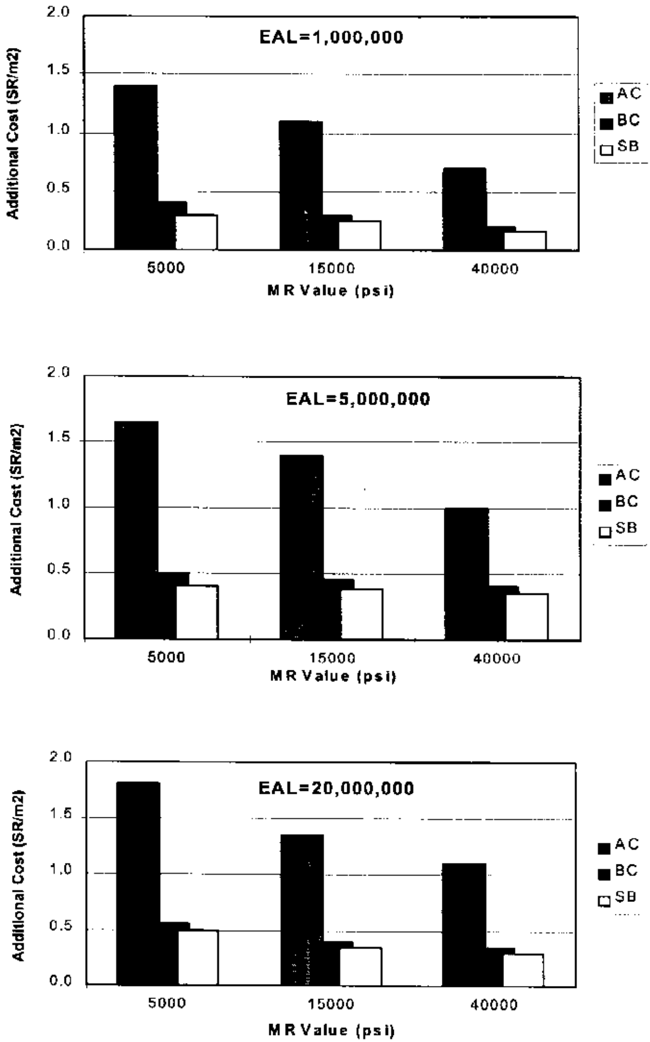

Fig. Additional costs resulting from excluding empty truck.

SR/m^2 for the granular subbase. Thus, under the assumption that the Riyadh area road network was designed using loaded truck factors, about 84 million SR could have been saved.

References

[1] Yoder, E.J. and Witczak, M.W. *Principles of Pavement Design*. 2nd ed., New York: John Wiley and Sons, Inc., 1975.

[2] Highway Research Board. *The AASHTO Road Test: Report 5-Pavement Research,* HRB Special Report 61-E, 1962.

[3] The Asphalt Institute. "Research and Development of the Asphalt Institute's Thickness Design Manual. (MS-1), Research Report No. 82-2, 9th ed., 1981.

[4] Deacon, J. A. "Load Equivalency in Flexible Pavements." *Proceedings, Association of Asphalt Paving Technologists*, Vol. 38, (1969) , 465-491.

[5] Federal Highway Administration. "*Highway Pavements.*" National Highway Institute, 1990.

[6] Al-Mansour, A. I. and Sharaf, E. A., "Analysis of Operational Levels of Truck Tire Pressure on the Kingdom's Road Network." Final Report No. C07/14/15, Research Center, College of Engineering, King Saud University, 1994.

[7] Sharaf, E. A., Arafah, A., Noureldin, A. S. and Alsugair, F. "Analysis of the Variability of the Predicted Design Equivalent Single Axle Load Applications in Saudi Arabia." The Second International Conference on Road & Airfield Pavement Technology." Singapore, 1995.

[8] American Association of State Highway and Transportation Officials. AASHTO Guide for Design of Pavement Structure. Washington D.C., 1986.

[9] Sharaf, E., Al-Suhaibani, A. and Al-Matham, S. "Analysis of the Effect of Deferring Preventive Maintenance: A Case Study on the Riyadh Road Network." The Symposium on Maintenance of Buildings - Public Structures and Preventive Measures, Makkah, 1996.

تأثير اعتبار المعامل المعدّل للشاحنات الفارغة على تصميم الرصف
(دراسة حالة على شبكة شوارع مدينة الرياض)

عصام عبدالعزيز شرف و عبدالله إبراهيم المنصور
قسم الهندسة المدنية، كلية الهندسة، جامعة الملك سعود، ص.ب ٨٠٠،
الرياض ١١٤٢١، المملكة العربية السعودية

(أستلم في ١٩٩٥/١٢/٤م ؛ وقُبل للنشر في ١٩٩٦/١٢/٧م)

ملخص البحث. يعتبر معامل الشاحنات أحد المدخلات الأساسية في عملية تصميم الرصف و يُعبر عن هذا المعامل في طرق التصميم من خلال الحمل المحوري المكافىء التراكمي حيث يعتمد على القيم السائدة لمعامل الشاحنات ، لذلك فانه من المهم تقدير قيم معامل الشاحنات بطريقة صحيحة على أساس الوضع المحلي لتحميل الشاحنات.

يعتمد الوضع القائم الآن في وزارة المواصلات على تسجيل الحمل المحوري للشاحنات المحمّلة فقط دون الشاحنات الفارغة ، و هذا يؤدي بدوره إلى تقدير أكبر لمعامل الشاحنات و بالتالي إلى تصميم أعلى من المطلوب.

تهدف هذه الدراسة إلى حساب تأثير استثناء الشاحنات الفارغة عند تقدير معامل الشاحنات على التصميم الإنشائي للرصف. لقد تم حساب معامل الشاحنات المحمّلة من ملفات المعلومات المتوافرة في وزارة المواصلات أما معامل الشاحنات الفارغة فقد تمّ حسابه عن طريق أخذ عينة للشاحنات الفارغة بلغت حوالي ٤٠٠٠ شاحنة و من ثم تمّ حساب المعامل المعدل للشاحنات الفارغة باستخدام المتوسط الموزون لمعامل الشاحنات المحملة و معامل الشاحنات الفارغة. و لقد تم دراسة تأثير استخدام المعامل المعدل للشاحنات الفارغة على التصميم الإنشائي للرصف باستخدام طريقة الاشتو.

لقد بينت هذه الدراسة أن متوسط معامل الشاحنات الفارغة حوالي ١,١٥ و متوسط معامل الشاحنات المحمّلة حوالي ٩,٨٧ أما متوسط المعامل المعدل للشاحنات الفارغة فقد بلغ حوالي ٦,٦٣ . كما أظهرت الدراسة أن استثناء الشاحنات الفارغة عند حساب معامل الشاحنات يؤدي إلى تصميم إنشائي أعلى من المطلوب تبلغ التكلفة الزائدة له حوالي ريال لكل متر مربع أو ٣٥٠٠ ريال لكل كيلومتر مسار.