# Damaging Effect of Tracked Armoured Vehicles on Flexible Pavement

**Dr. Saud A. Sultan***

Received on: 27/3/2009
Accepted on: 1/7/2010

**Abstract**

Presented in this paper is a new study of the AASHTO equivalency factors of military tracked armoured vehicles on flexible pavement. Two types of military tracked armoured vehicles were studied, namely Challenger 2 tank and MT-LB-T tracked armoured vehicle. A measure of the damaging effect of military tracked armoured vehicle loads was achieved by correlating their equivalent loads with the AASHTO equivalency factors. The equivalent load was developed on the basis of mechanistic - empirical approach. It was found that the damaging effect of the studied military tracked armoured vehicle loads is 0.039 to 5.750 times the damaging effect of the standard 18 kips (80 kN) axle load depending on the thickness of asphalt layer. It was found that the damaging effect of military tracked armoured vehicle loads on flexible pavements of major highways and main principal roads is much more than its damaging effect on the flexible pavement of local and secondary roads. It was found also, that tracked armoured vehicles have a severe damaging effect on the functional serviceability of surface asphalt layer in terms of deformation and strains due to the effect of rigid track chain.

**Keywords:** military tracked armoured vehicles, AASHTO equivalency factors, flexible pavements, and damaging effect.

## التأثير التخريبي لأحمال ألعجلات المدرعة المسرفة على التبليط ألإسفلتي

**الخلاصة**

دراسة جديدة للتأثير التخريبي لأحمال ألعجلات المدرعة المسرفة على التبليط الإسفلتي من خلال أبجاد معاملات آشتو المكافئة لها ولأول مرة وباستخدام طريقة الحل الميكانيكي – التجريبي. لقد وجد إن تأثير الأحمال التخريبي للعجلات المدرعة المسرفة التي تمت دراستها يتراوح من 0.039 إلى 5.750 مرة تأثير حمل آشتو القياسي حسب سمك طبقة الإسفلت. لقد وجد إن تأثير الأحمال التخريبي للعجلات المدرعة المسرفة أكثر بكثير على الطرق الرئيسية مما هو على الطرق الثانوية. لقد وجد إن للعجلات المدرعة المسرفة تأثير تخريبي على الخواص الوظيفية لطبقة الإسفلت السطحية بسبب السرف الصلبة.

## 1. Introduction

The growth in truck traffic volumes as observed over the past few decades, combined with increasing commercial vehicle weights and dimensions, is causing the anticipated lifespan of many roadways to decrease (World Road Association, 2004). Consequently projected maintenance and preservation costs increase. Pavement deterioration is further intensified by an incentive for overweight trucks due to economic benefits of an increased payload (Paxson and Glickert, 1982). Faced with the decreasing lifespan of their infrastructure, roadway agencies are investigating low-cost but effective methods of monitoring and enforcement [(3)]. The effect of the traffic using these roads should be focused upon carefully from the standpoint of pavement structural design. Yoder and Witczak (1975)

* Engineering College, University of Al Mustansyria / Baghdad

reported that this effect includes among other considerations, the expected vehicle type and the corresponding number of repetitions of each type during the design life of the pavement. The effect of various types of vehicles (axles) on the structural design of road pavement is considered by means of the approach of axle load equivalency factor. In this approach, a standard axle load is usually used as a reference and the damaging effect of all other axle loads (corresponding to various types of axles) is expressed in terms of number of repetitions of the standard axle.

The AASHTO standard axle is the 18 kips (80 kN) single axle with dual tires on each side (Saskatchewan Department of Highways and Transportation (SDHT), 2006). Thus, the AASHTO equivalency factor defines the number of repetitions of the 18 kips (80 kN) standard axle load which causes the same damage on pavement as caused by one pass of the axle in question moving on the same pavement under the same conditions.

The AASHTO equivalency factor depends on the axle type (single, tandem, or triple), axle load magnitude, structural number (SN), and the terminal level of serviceability (pt). The effect of structural number (SN) and the terminal level of serviceability (pt) are rather small; however, the effect of axle type and load magnitude is pronounced (Razouki and Hussain 1985). There are types of vehicle loads that not included in the AASHTO road test such as the heavy military tracked armoured vehicles that move on paved roads occasionally during peace times and frequently during war times. **The effect of the tracked armoured vehicle loads on flexible pavement is not known, and not mentioned in the literature up to the capacity of the author's knowledge**. Therefore, this research was carried out to find the AASHTO equivalency factors and the damaging effect of tracked armoured vehicles that move frequently on our roads network (even on small local paved streets) on daily bases for more than six years up to now. There are two main approaches used by researchers to determine the equivalency factors, the experimental and the mechanistic (theoretical) approach. A combination of two approaches was also used by Wang and Anderson (1979). In the mechanistic approach, some researchers adopted the fatigue concept analysis for determining the destructive effect (Havens et al., 1979), while others adopted the equivalent single wheel load procedure for such purposes (Kamaludeen, 1987).The mechanistic empirical approach is used in this research depending on fatigue concept.

Following Yoder and Witczak (1975), AASHTO design method recommended the use of 18 kips (80 kN) standard axle with dual tires on each side, thus, AASHTO equivalency factor $F_j$ is:

$$F_j = \left(\frac{\varepsilon_j}{\boldsymbol{\varepsilon_s}}\right)^{\mathbf{c}} \qquad \text{..... (1)}$$

where, $\varepsilon_j$ , $\varepsilon_s$ = the maximum principal tensile strain for the jth axle and the 18 kips standard single axle respectively, and c represent regression constant. Yoder and Witczak (1975) reported that both laboratory tests and field studies have indicated that the constant c ranges between 3 and 6 with common values of 4 to 5.

Van Til et al. (1972) and AASHTO (1986) recommended two fatigue criteria for the determination of AASHTO equivalency factors namely, the tensile strain at the bottom fiber of asphalt concrete and the vertical strain on sub-grade surface. AASHTO (1986) reported a summary of calculations for tensile strain at the bottom fiber of asphalt concrete (as fatigue criterion) due to the application of 18 kips standard axle load on flexible pavement structures similar to that of original AASHTO road test pavements. Also, AASHTO (1986) reported a summary of calculations for vertical compressive strain on sub-grade surface (as rutting criterion) due to the application of 18 kips standard axle load on flexible pavement structures similar to that of original AASHTO road test pavements. The AASHTO (1986) calculated strains are function of the structural number

(SN), the dynamic modulus of asphalt concrete, the resilient modulus of the base materials, the resilient modulus of roadbed soil, and the thickness of pavement layers. These reported AASHTO (1986) strains which represent ($\varepsilon_s$) in equation (1) above in addition to Van Til et al. (1972) & Huang (1993) reported experimental values for the constant c in equation (1) above for different pavement structures. (1993) reported that in fatigue analysis, the horizontal minor principal strain is used instead of the overall minor principal strain. This strain is called minor because tensile strain is considered negative. Horizontal principal tensile strain is used because it is the strain that causes the crack to initiate at the bottom of asphalt layer. The horizontal principal tensile strain is determined from:

$$\varepsilon_r = \frac{\varepsilon_x + \varepsilon_y}{2} - \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \gamma_{xy}^2} \quad \ldots (2)$$

where, $\varepsilon_r$ = the horizontal principal tensile strain at the bottom of asphalt layer, $\varepsilon_x$ = the strain in the x direction, $\varepsilon_y$ = the strain in the y direction, $\gamma_{xy}$ = the shear strain on the plane x in the y direction. Therefore, ($\varepsilon_r$) of equation (2) represents ($\varepsilon_j$) of equation (1) and will be used in fatigue analysis in this research. These two criteria were used in this research to determine the AASHTO equivalency factors of tracked armoured vehicles. The tensile strains at the bottom fiber of asphalt concrete and vertical compressive strains on sub-grade surface of similar pavement structures to that of AASHTO road test as reported by AASHTO (1986) were calculated under tracked armoured vehicles in this research. Also, a comparison was made between different calculated three-direction strains under tracked armoured vehicles on the surface of flexible pavement and that of AASHTO 18 kips standard axle to study the damaging effect of these tracked armoured vehicles on the functional features of the asphalt layer. KENLAYER linear elastic computer program (Huang, 1993) was used to calculate the required strains and stresses in this research at 400 points each time in three dimensions at different locations within AASHTO reported pavement structures under tracked armoured vehicles.

**2- Characteristics of tracked armoured vehicles**

Two types of military tracked armoured vehicles were used in this research, namely, Challenger 2 tank and MT-LB-T armoured vehicle because they are widely used world wide. The characteristics of tracked armoured vehicles which required in this research are their three dimensions (height, length, and width) in addition to weight. The width and length of the tracked armoured vehicle track in contact with the surface of flexible pavement are required, also. These features were obtained from the brochure of the manufacturing companies (Vickers Defense Systems, 2010, Caterpillar Defense & Federal Products, 2010, General Dynamics Land Systems, 2010 and The Federation of American Scientists, 2010). The width and the length of the track in contact with the surface of asphalt pavement were measured from the available tracked armoured vehicle markings on the surface of asphalt concrete pavements at different locations. Figure (1), Table (1), and Figure (2) were prepared to show the obtained characteristics of the two military tracked armoured vehicles. It was found that the actual track width of Challenger 2 (in contact with the surface of asphalt pavement) is 24 inch (61 cm) to 28 inch (71 cm) on each side. This track is not in full contact with the pavement, there are openings depending on the type and way these tracks are manufactured as shown in Figure (1). Therefore, the effect of the shape and width of the track contact area will be studied to investigate their effect on the results.

**3- Analysis Methodology**

**3-1 The simulation of military tracked armoured vehicle loads**

**3-1-1 The simulation of Challenger 2 tank load**

The length of the track of the Challenger 2 tank that in direct contact with the ground was taken as 5.20 m as shown in Figure (2) above. This length value was obtained from the brochure of the manufacturing company(Vickers Defense Systems, 2010, and Caterpillar Defense &

Federal Products, 2010) and the website (The Federation of American Scientists, 2010), in addition to that this width value was found to be almost equal to that measured from markings left on the surface of asphalt layer at different locations. Two values for the width of the Challenger 2 track were taken in the analysis namely, 0.61 m and 0.71 m because when the tracked armoured vehicle moves on soft ground (earth surface), the whole width of the track (0.71 m) is involved in transferring the tracked armoured vehicle loads but when it moves on paved roads the inner solid plates of the track (0.61 m) are involved mainly in transferring the tracked armoured vehicle loads to the ground, see Figure (1) above. Two types of contact area were taken in this analysis to simulate the distribution of Challenger 2 loads on the surface of flexible pavement for analysis purposes, as shown in Figures (4) below. The first type shown in Figure (4) represents the (0.61 m x 5.20 m) track on each side of the Challenger 2. This track contact area (on each side of the Challenger 2 tank) was simulated by 40 circular areas with a radius of (0.096 m) each to take the contact solid plates of the track into consideration and to keep the same Challenger 2 tank load without change. The second type shown in Figure (4) represents the (0.71 m x 5.20 m) track on each side of the Challenger 2 tank load. This track area was simulated by 9 circular areas on each side of the Challenger 2 tank with a radius of (0.29 m) each to take the maximum contact width of the track into consideration and to keep the same Challenger 2 tank load without change.

**3-1-2 The simulation of MT-LB-T military tracked armoured vehicle load**

MT-LB-T multipurpose armoured vehicle was used as the second type of military tracked armoured vehicles that is widely used world wide [16]. The length of the track of the MT-LB-T armoured vehicle that in direct contact with the ground was taken as 4.10 m as shown in Figure (3) above. This length value was obtained from the brochure of the manufacturing company (Caterpillar Defense & Federal Products, 2010 and General Dynamics Land Systems, 2010)) and the website (The Federation of American Scientists, 2010) in addition to that; this width value was found to be almost equal to that measured from markings left on the surface of asphalt layer at different locations. Two types of contact area were taken in the analysis to simulate the distribution of MT-LB-T armoured vehicle loads on the surface of flexible pavement for analysis purposes, as shown in Figures (5) below. The first type shown in Figure (5) represents the (0.35 m x 4.10 m) track on each side of the MT-LB-T armoured vehicle. This track contact area (on each side of the MT-LB-T armoured vehicle) was simulated by 40 circular areas with a radius of (0.078 m) each to take the contact solid plates of the track into consideration and to keep the same MT-LB-T armoured vehicle load without change. The second type shown in Figure (5) represents the (0.55 m x 4.10 m) track on each side of the MT-LB-T armoured vehicle. This track area was simulated by 9 circular areas on each side of the MT-LB-T armoured vehicle with a radius of (0.176 m) each to take the maximum contact width of the track into consideration and to keep the same MT-LB-T armoured vehicle load without change.

**3-2 AASHTO equivalency factors of military tracked armoured vehicles**

Three-layer pavement structure was taken as mentioned in the introduction above to simulate AASHTO original road test pavements as shown in Figure (3). Only one set of values for the modulus of asphalt layer ($E_1$=1035.5 MPa), the base layer ($E_2$=103.5 MPa), and the sub-grade modulus ($E_3$=51.7 MPa) was taken from the original AASHTO road test because it is similar to the modulus values of local materials in practice (Kamaludeen, 1987). AASHTO Poisson's ratios of 0.4 for asphalt layer, 0.35 for base layer, and 0.4 for sub-grade layer were taken for the purpose of this analysis.

**3-2-1 AASHTO equivalency factors of Challenger 2 tank load**

Figure (6), Figure (7), and Figure (8) were prepared to show the calculated tensile strains in the direction of x, y, and r at the bottom fiber of asphalt concrete layer respectively under the Challenger 2 tank load. These calculated strains were for the AASHTO pavement structure shown in Figure (3) and for the simulation type 1 shown in Figure (4) above for the layout of Challenger 2 tank load. These strains were obtained for 400 calculating points for each one of these Figures using KENLAYER computer program (Huang, 1993). Figure (9) was prepared to show the calculated vertical compressive strains on the surface of sub-grade layer of AASHTO pavement structure shown in Figure (3) under Challenger 2 tank load. These strains were obtained for 400 calculating points using KENLAYER computer program (Huang, 1993). It was found that the calculated vertical compressive strains on the surface of sub-grade layer under Challenger 2 tank load are much more conservative than calculated tensile strains in the direction of x, y, and r at the bottom fiber of asphalt concrete layer in comparison with their similar type of strains reported by AASHTO (1986), as shown in Figure (6) to Figure (9).Therefore, the rutting criterion governed and was used to calculate the AASHTO equivalency factors of Challenger 2 tank load. The maximum calculated vertical compressive strains on the surface of sub-grade layer under Challenger 2 tank load for the AASHTO (1986) pavement structures are summarized in Table (2). The AASHTO (1986) reported maximum vertical compressive strains on the surface of sub-grade layer for the AASHTO pavement structures under the standard 18 kips (80 kN) are shown also in Table (2). The values for the constant c of equation (1) for each one of AASHTO (1986) pavement structures were obtained from Van Til et. al. (1972). The AASHTO equivalency factors of Challenger 2 tank load were calculated using equation (1) are shown in Table (2).

**3-2-1-1 Effect of Challenger 2 tank track width on AASHTO equivalency factors**

The maximum vertical compressive strains on the surface of sub-grade layer under Challenger 2 tank load for the AASHTO (1986) pavement structures were recalculated using type 2 layout for the simulation of as shown in Figure (4) above and for the pavement structure shown in Figure (3) above. This recalculation was carried out to investigate the effect of the track width on the AASHTO equivalency factors. Table (3) was prepared to show the AASHTO equivalency factors of Challenger 2 tank load based on the same variables used in preparing Table (2) but with the use of type 2 layout for the simulation of Challenger 2 tank load.

**3-2-2 AASHTO equivalency factors of MT-LB-T armoured vehicle load**

The same procedure mentioned in paragraph 3-2-1 above to determine the AASHTO equivalency factors of Challenger 2 tank load was repeated to determine the AASHTO equivalency factors of MT-LB-T armored vehicle except that the dimensions and weight of MT-LB-T armored vehicle were used instead of the dimensions and weight of Challenger 2 tank. Also, the effect of track width of MT-LB-T armoured vehicle on AASHTO equivalency factors was studied. Table (4) and Table (5) were prepared following the same procedure in preparing Table (2) and Table (3) to show the AASHTO equivalency factors of MT-LB-T armored vehicle load. Also, the rutting criterion governed and was used to calculate the AASHTO equivalency factors of MT-LB-T armoured vehicle load. The maximum calculated vertical compressive strains on the surface of sub-grade layer under MT-LB-T armoured vehicle load for the AASHTO (1986) pavement structures are summarized in Table (4) and Table (5).

**3-3 Damaging effect of tracked armoured vehicles on the surface of asphalt layer**

Besides the structural damaging effect of tracked armoured vehicle loads on flexible pavement structures in terms of rutting and fatigue cracking, there is another damaging effect on the functional properties of the surface of the asphalt concrete layers i.e. the permanent deformations in the three directions and distress due to the movement of the rigid track chain on the relatively softer asphalt layer surface. Figure (10) to Figure (12) were prepared to show the strains in the direction of x, y, and z at the surface of asphalt layer respectively under Challenger 2 tank load on AASHTO pavement structure shown in Figure (3) using type 1 load simulation shown in Figure (4) above. Figure (13) was prepared to show shear strain in the direction of (xy) at the surface of asphalt layer under Challenger 2 tank load on AASHTO pavement structure shown in Figure (3) using type 1 load simulation shown in Figure (4). Table (6) was prepared to compare the displacements at the surface of asphalt layer under Challenger 2 tank with that reported by AASHTO[10] 18 kips (80 kN) standard axle load on the same original AASHTO road test pavements.

## 4- Discussion of results and Conclusions

It was found that military tracked armoured vehicles have a pronounced damaging effect on flexible pavements in terms of AASHTO equivalency factors as follows:

1- The AASHTO equivalency factors of Challenger 2 tank load were found to be from 0.962 to 5.750 based on rutting criterion. Increasing the thickness of the asphalt layer pavement increases the AASHTO equivalency factors of Challenger 2 tank load. This means that the structural damaging effect of Challenger 2 tank load on flexible pavements of major highways and main principal roads is much more than its damaging effect on the flexible pavement of local and secondary roads. It was found that increasing the width of track or the layout of Challenger 2 tank loads has a small effect from the theoretical point of view due to the high magnitude of the Challenger 2 tank load. Practically speaking, AASHTO equivalency factors of Challenger 2 tank load calculated using type 1 Challenger 2 tank loads layout are more accurate than those calculated using type 2 loads layout because the track (contact area) is not in full contact with the surface of paved roads as shown in Figure (1). It was found also, that Challenger 2 tank load has a severe damaging effect on the functional serviceability of surface of asphalt layer in terms of deformation and strains due to the effect of relatively rigid track chain in comparison of asphalt surface.

2- The AASHTO equivalency factors of MT-LB-T armored vehicle load were found to be from 0.039 to 0.338 based on rutting criterion. Increasing the thickness of the asphalt layer pavement increases the AASHTO equivalency factors of MT-LB-T armored vehicle load. This means that the structural damaging effect of MT-LB-T armored vehicle load on flexible pavements of major highways and main principal roads is much more than its damaging effect on the flexible pavement of local and secondary roads. MT-LB-T armored vehicle load has a severe damaging effect on the functional serviceability of surface of asphalt layer in terms of deformation and strains due to the effect of relatively rigid track chain in comparison of asphalt surface in spite of its small AASHTO equivalency factors AASHTO equivalency factors.

## 6- Recommendations

Based on the results of this study, an economic evaluation for the cost of damage that had been caused by the frequent movement of military tracked armoured vehicles on the national road network during the last six years is required. Another study is necessary to determine the damaging effect of military tracked armoured vehicles on the national road network during summer seasons.

## Notations

- $F_j$ AASHTO equivalency factor.
- c regression constant.
- $E_1$ the modulus of asphalt layer.
- $E_2$ the modulus of the base layer.
- $E_3$ the modulus of subgrade layer.
- $t_1$ thickness of asphalt layer.
- $t_2$ thickness of base layer.

## Greek letters

- $\varepsilon_j$ the maximum principal tensile strain for the jth axle.
- $\varepsilon_s$ the maximum principal tensile strain for the 18 kips standard single axle.

$\varepsilon_r$ the horizontal principal tensile strain at the bottom of asphalt layer.
$\varepsilon_x$ the strain in the x direction.
$\varepsilon_y$ the strain in the y direction.
$\gamma_{xy}$ the shear strain on the plane x in the y direction.
$\varepsilon_v$ compressive strain on the top of subgrade soil..
$\varepsilon_t$ tensile strain at the bottom of asphalt layer.
$\mu_1$ Poisson's ratio of asphalt layer.
$\mu_2$ Poisson's ratio of the base layer
$\mu_3$ Poisson's ratio of subgrade layer.

**References**

**[1]** World Road Association, (2004), "Vehicle Size and Weight Limits Experiences and Trends", Permanent International Association of Road Congresses, (PIARC) Technical Committee on Freight Transport (C19).

**[2]** Paxson, D.S., and J.P. Glickert, (1982) "Value of Overweighting to Intercity Truckers", Transportation Research Record, No. 889, Transportation Research Board: 33 – 37.

**[3]** Saskatchewan Department of Highways and Transportation (SDHT). "2005-2006 Provincial Budget Performance Plan". Online. Internet, May19, 2005.

**[4]** Yoder, E. J., and Witczak, M. W., (1975), "Principles of pavement design ", 2nd edition, John Wiley and Sons, Inc., New York.

**[5]** Razouki, S. S., and Hussain, S. F., (1985) "Equivalency factors for floating tandem axle loads on flexible pavements", Proceedings, Iraqi Conference on Engineering, ICE 85, College of Engineering, University of Baghdad, vol. 1, Baghdad,.

**[6]** Wang, M.C., and Anderson, R. P., (1979), "Load equivalency factors for triaxial loading for flexible pavements", TRB record 725.

**[7]** Havens, J. H., Southgate, H.F., and Deen, R, C, (1979), "Fatigue damage to flexible pavements under heavy loads", TRB record 725.

**[8]** Kamaludeen, N. M., (1987), "Damaging effect of triple axle loads on flexible pavements", M.Sc. thesis, College of Engineering, University of Baghdad, Baghdad.

**[9]** Van Til , C. J., McCullough, B. F., Vallerga, B. A., and Hicks, R. G. , (1972), "Evaluation of AASHTO interim guides for design of pavement structures", Highway Research Board, NCHRP report 128, Washington D.C.

**[10]** AASHTO, (1986), "AASHTO guide for the design pavement structures 1986", The American Association of State Highway Transportation Officials, Washington D.C.

**[11]** Huang, Yang H., (1993), "Pavement analysis and design", 1st. edition, Prentice Hall, Inc., New Jersey, USA.

**[12]** Vickers Defense Systems, (2010), "Challenger 2 – Main Battle Tank", Manson Lane, Crossgates, Leeds, West Yorkshire LS15 8ST, United Kingdom, http://www.army-guide.com/eng/product408.html

**[13]** Vickers Defense Systems, Inc., (2010), http://www.vickersdefence.co.uk/challenger2.htm".

**[14]** Caterpillar Defense & Federal Products, (2010), PO Box 470, Mossville, IL 61552-0470, USA, www.cat.com.

**[15]** General Dynamics Land Systems, Inc., 38500 Mound Road Sterling Heights, MI 48310-3200, USA, www.gdls.com.

**[16]** The Federation of American Scientists, (2010), "Military armoured vehicles", Military Analysis Network, http:// www.fas.org.

.

Table (1): Characteristics of tracked armoured vehicles.

| Feature | Type of tracked armoured vehicle | |
|---|---|---|
| | CHALLENGER 2 | MT-LB-T |
| Length (m) | 8.30 | 4.86 |
| Width (m) | 3.40 | 2.85 |
| Height Turret (m) | 2.50 | 1.87 |
| Combat Weight (ton) | 62.5 | 26.25 |
| Speed (km/h) | 80 | 70 |

Table (2): AASHTO equivalency factors of Challenger 2 tank using rutting criterion and for tank load simulation type 1 (Figure (4)).

| Modulus Layer 1 = 1035.5 MPa, $\mu_1$ = 0.40 | | | | | | |
|---|---|---|---|---|---|---|
| Modulus Layer 2 = 103.5 MPa, $\mu_2$ = 0.35 | | | | | | |
| Modulus Layer 3 = 51.724 MPa, $\mu_3$ = 0.40 | | | | | | |
| Thickness Layer 1 cm | Thickness Layer 2 cm | Source of Data | Vertical strain ($\varepsilon_z$) on sub-grade | SN | c | Challenger2 AASHTO Equivalency Factor |
| 7.62 | 56.64 | AASHTO(1) | 0.0004330 | 4 | 3.54 | 1.505 |
| 7.62 | 56.64 | Calculated(2) | 0.0004860 | 4 | 3.54 | 1.505 |
| 10.16 | 47.50 | AASHTO(1) | 0.0005280 | 4 | 3.43 | 0.962 |
| 10.16 | 47.50 | Calculated(2) | 0.0005220 | 4 | 3.43 | 0.962 |
| 12.70 | 59.18 | AASHTO(1) | 0.0003420 | 5 | 3.43 | 2.373 |
| 12.70 | 59.18 | Calculated(2) | 0.0004400 | 5 | 3.43 | 2.373 |
| 15.24 | 50.04 | AASHTO(1) | 0.0003740 | 5 | 3.43 | 2.126 |
| 15.24 | 50.04 | Calculated(2) | 0.0004660 | 5 | 3.43 | 2.126 |
| 20.32 | 52.58 | AASHTO(1) | 0.0002940 | 6 | 4.29 | 4.572 |
| 20.32 | 52.58 | Calculated(2) | 0.0004190 | 6 | 4.29 | 4.572 |

(1) AASHTO (1986) maximum vertical strain($\varepsilon_z$) on the sub-grade surface under the standard 18 kips (80 kN) axle load for terminal of serviceability (Pt) of 2.0.

(2) Calculated maximum vertical strain($\varepsilon_z$) on the sub-grade surface under the Challenger 2 tank for type 1 simulated layout of tank loads shown in Figure (4) above.

Table (3): AASHTO equivalency factors of Challenger 2 tank using rutting criterion and for tank load simulation type 2 (Figure (4)).

| Modulus Layer 1 = 1035.5 MPa, $\mu_1$ = 0.40 | | | | | | |
|---|---|---|---|---|---|---|
| Modulus Layer 2 = 103.5 MPa, $\mu_2$ = 0.35 | | | | | | |
| Modulus Layer 3 = 51.7 MPa, $\mu_3$ = 0.40 | | | | | | |
| Thickness Layer 1 cm | Thickness Layer 2 cm | Source of Data | Vertical strain ($\varepsilon_z$) on sub-grade | SN | c | Challenger2 AASHTO Equivalency Factor |
| 7.62 | 56.64 | AASHTO(1) | 0.0004330 | 4 | 3.54 | 1.820 |
| 7.62 | 56.64 | Calculated(2) | 0.0005130 | 4 | 3.54 | 1.820 |
| 10.16 | 47.50 | AASHTO(1) | 0.0005280 | 4 | 3.43 | 1.246 |
| 10.16 | 47.50 | Calculated(2) | 0.0005630 | 4 | 3.43 | 1.246 |
| 12.70 | 59.18 | AASHTO(1) | 0.0003420 | 5 | 3.43 | 2.865 |
| 12.70 | 59.18 | Calculated(2) | 0.0004650 | 5 | 3.43 | 2.865 |
| 15.24 | 50.04 | AASHTO(1) | 0.0003740 | 5 | 3.43 | 2.650 |
| 15.24 | 50.04 | Calculated(2) | 0.0004970 | 5 | 3.43 | 2.650 |
| 20.32 | 52.58 | AASHTO(1) | 0.0002940 | 6 | 4.29 | 5.750 |
| 20.32 | 52.58 | Calculated(2) | 0.0004420 | 6 | 4.29 | 5.750 |

(1) AASHTO (1986) maximum vertical strain($\varepsilon_z$). (2) Calculated maximum vertical strain($\varepsilon_z$).

.

**Table (4): AASHTO equivalency factors of MT-LB-T military armoured vehicle using rutting criterion and for load simulation type 1 (Figure (5)).**

| Modulus Layer 1 = 1035.5 MPa, $\mu_1$ = 0.40 | | | | | | |
|---|---|---|---|---|---|---|
| Modulus Layer 2 = 103.5 MPa, $\mu_2$ = 0.35 | | | | | | |
| Modulus Layer 3 = 51.724 MPa, $\mu_3$ = 0.40 | | | | | | |
| Thickness Layer 1 cm | Thickness Layer 2 cm | Source of Data | Vertical strain $(\varepsilon_z)$ on sub-grade | SN | c | MT-LB-T AASHTO Equivalency Factor |
| 7.62 | 56.64 | AASHTO(1) | 0.0004330 | 4 | 3.54 | 0.219 |
| 7.62 | 56.64 | Calculated(2) | 0.0002820 | 4 | 3.54 | 0.219 |
| 10.16 | 47.50 | AASHTO(1) | 0.0005280 | 4 | 3.43 | 0.142 |
| 10.16 | 47.50 | Calculated(2) | 0.0002990 | 4 | 3.43 | 0.142 |
| 12.70 | 59.18 | AASHTO(1) | 0.0003420 | 5 | 3.43 | 0.280 |
| 12.70 | 59.18 | Calculated(2) | 0.0002360 | 5 | 3.43 | 0.280 |
| 15.24 | 50.04 | AASHTO(1) | 0.0003740 | 5 | 3.43 | 0.307 |
| 15.24 | 50.04 | Calculated(2) | 0.0002650 | 5 | 3.43 | 0.307 |
| 20.32 | 52.58 | AASHTO(1) | 0.0002940 | 6 | 4.29 | 0.336 |
| 20.32 | 52.58 | Calculated(2) | 0.0002280 | 6 | 4.29 | 0.336 |

(1) AASHTO (1986) maximum vertical strain $(\varepsilon_z$

(2) Calculated maximum vertical strain $(\varepsilon_z)$

**Table (5): AASHTO equivalency factors of MT-LB-T armoured vehicle using rutting criterion and for MT-LB-T load simulation type 2(Figure (5)).**

| Modulus Layer 1 = 1035.5 MPa, $\mu_1$ = 0.40 | | | | | | |
|---|---|---|---|---|---|---|
| Modulus Layer 2 = 103.5 MPa, $\mu_2$ = 0.35 | | | | | | |
| Modulus Layer 3 = 51.7 MPa, $\mu_3$ = 0.40 | | | | | | |
| Thickness Layer 1 cm | Thickness Layer 2 cm | Source of Data | Vertical strain $(\varepsilon_z)$ on sub-grade | SN | c | MT-LB-T AASHTO Equivalency Factor |
| 7.62 | 56.64 | AASHTO(1) | 0.0004330 | 4 | 3.54 | 0.039 |
| 7.62 | 56.64 | Calculated(2) | 0.0001730 | 4 | 3.54 | 0.039 |
| 10.16 | 47.50 | AASHTO(1) | 0.0005280 | 4 | 3.43 | 0.087 |
| 10.16 | 47.50 | Calculated(2) | 0.0002590 | 4 | 3.43 | 0.087 |
| 12.70 | 59.18 | AASHTO(1) | 0.0003420 | 5 | 3.43 | 0.314 |
| 12.70 | 59.18 | Calculated(2) | 0.0002440 | 5 | 3.43 | 0.314 |
| 15.24 | 50.04 | AASHTO(1) | 0.0003740 | 5 | 3.43 | 0.295 |
| 15.24 | 50.04 | Calculated(2) | 0.0002620 | 5 | 3.43 | 0.295 |
| 20.32 | 52.58 | AASHTO(1) | 0.0002940 | 6 | 4.29 | 0.338 |
| 20.32 | 52.58 | Calculated(2) | 0.0002320 | 6 | 4.29 | 0.338 |

(1) AASHTO (1986) maximum vertical strain $(\varepsilon_z)$ on the sub-grade surface under the standard 18 kips (80 kN) axle load for terminal of serviceability (Pt) of 2.0.

(2) Calculated maximum vertical strain $(\varepsilon_z)$ on the sub-grade surface under the MT-LB-T military armoured vehicle for type 2 simulated layout of MT-LB-T loads shown in Figure (5) above.

.

**Table (6): Maximum displacements at the surface of asphalt layer under AASHTO 18 kips and Challenger 2 tank.**

| Modulus Layer 1 = 1035.5 MPa, $\mu_1$ = 0.40 | | | | |
|---|---|---|---|---|
| Modulus Layer 2 = 103.5 MPa, $\mu_2$ = 0.35 | | | | |
| Modulus Layer 3 = 51.7 MPa, $\mu_3$ = 0.40 | | | | |
| Thickness Layer 2 cm | Thickness Layer 2 cm | Load Type | Deformation Type | Deformation Value (mm) |
| 7.62 | 56.64 | 18 kips | displacement x | 0.075946 |
| 7.62 | 56.64 | Tank | displacement x | 0.138430 |
| 7.62 | 56.64 | 18 kips | displacement y | 0.073406 |
| 7.62 | 56.64 | Tank | displacement y | 0.128016 |
| 7.62 | 56.64 | 18 kips | displacement z | 0.101346 |
| 7.62 | 56.64 | Tank | displacement z | 2.37744 |

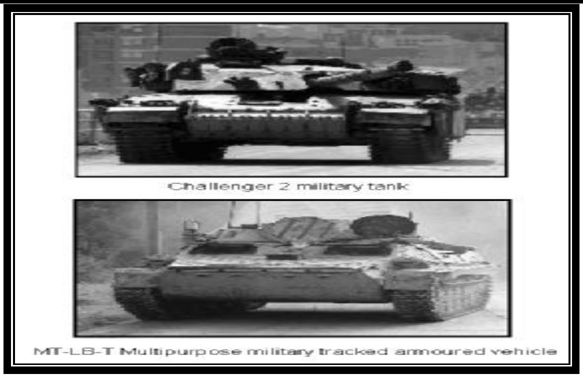


**Figure (1): Tracked armoured vehicles.**

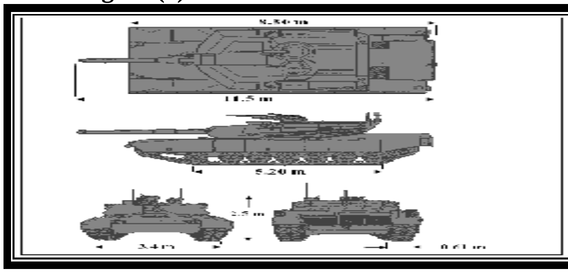

**Figure (2): Dimensions of Challenger 2 tank**

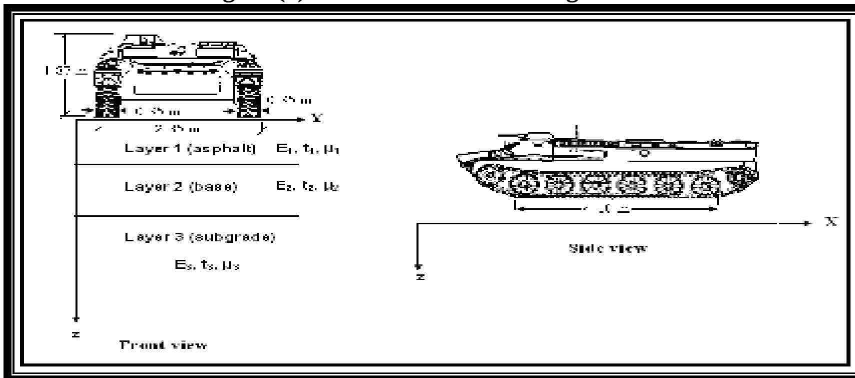


**Figure (3): Dimensions of MT-LB-T racked armoured vehicle.**

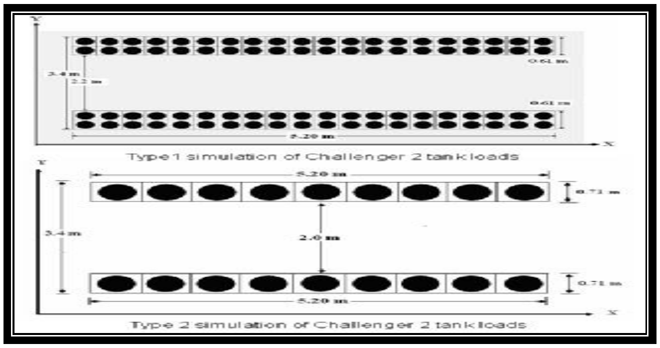


Figure (4): Type1 and 2 simulation of the distribution of Challenger 2 loads on the surface of flexible pavement for analysis purposes.

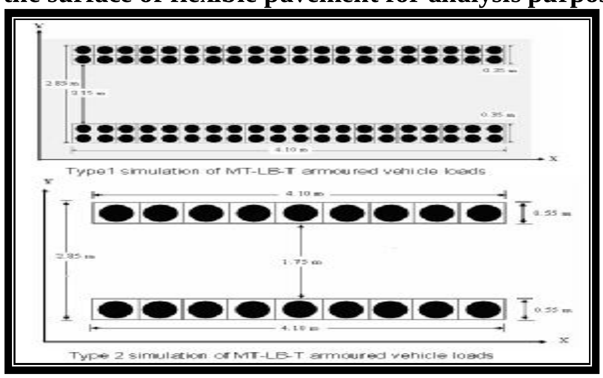


Figure (5): Type 1 and 2 simulation of the distribution of MT-LB-T loads on the surface of flexible pavement for analysis purposes.

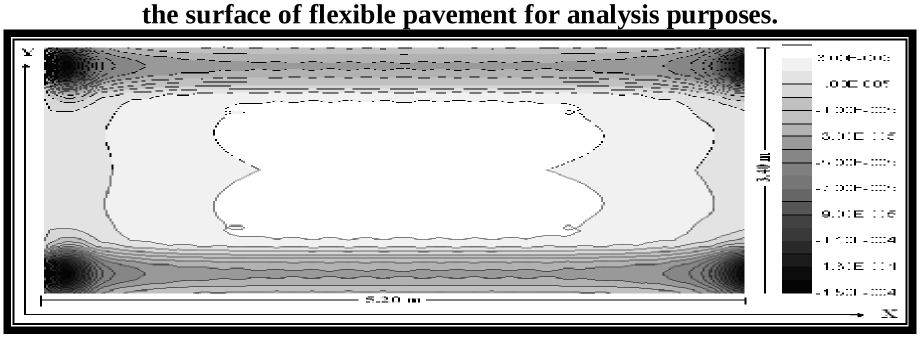


Figure (6): Tensile strain in the x direction $(\varepsilon_x)$ at the bottom fiber of asphalt layer ($t_1$=7.6 cm and $t_2$=56.6 cm).

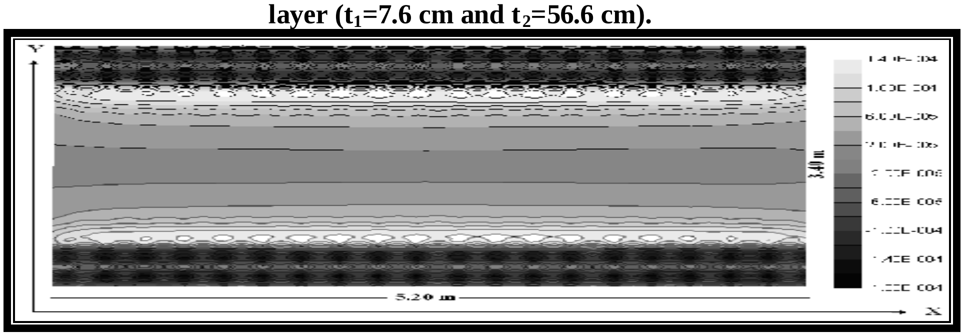


Figure (7): Tensile strain in the y direction $(\varepsilon_y)$ at the bottom fiber of asphalt layer ($t_1$=7.6 cm and $t_2$=56.6 cm).

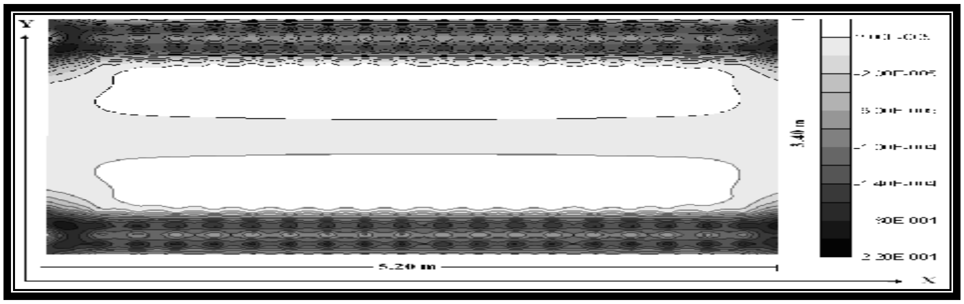


**Figure (8): Horizontal principal tensile strain at the bottom of asphalt layer ($\varepsilon_r$) ($t_1$=7.6 cm & $t_2$=56.6 cm).**

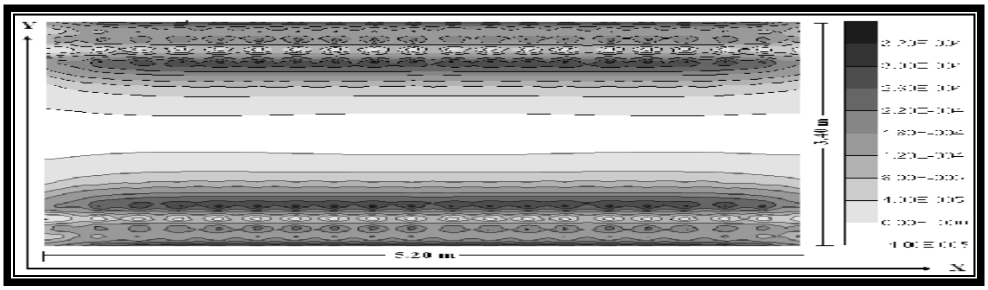


**Figure (9): Vertical strain in the z direction ($\varepsilon_z$) on the surface of sub-grade layer ($t_1$=7.6 cm & $t_2$=56.6 cm).**

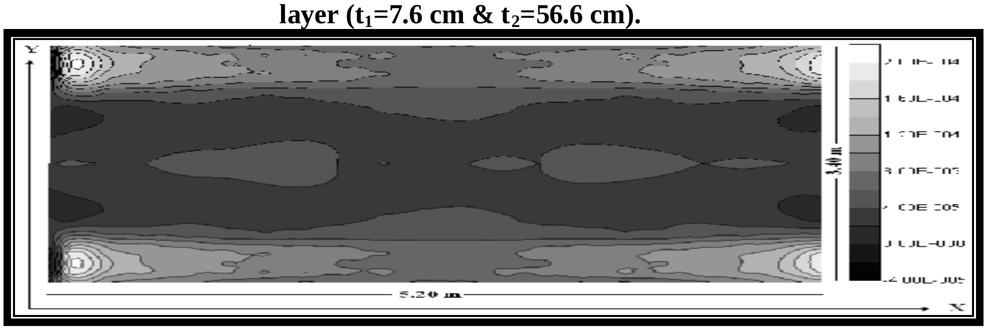


**Figure (10): Strains in the x direction at the surface of asphalt layer under the tank loads for the pavement structure in Figure (5), ($t_1$=7.6 cm & $t_2$=56.6 cm).**

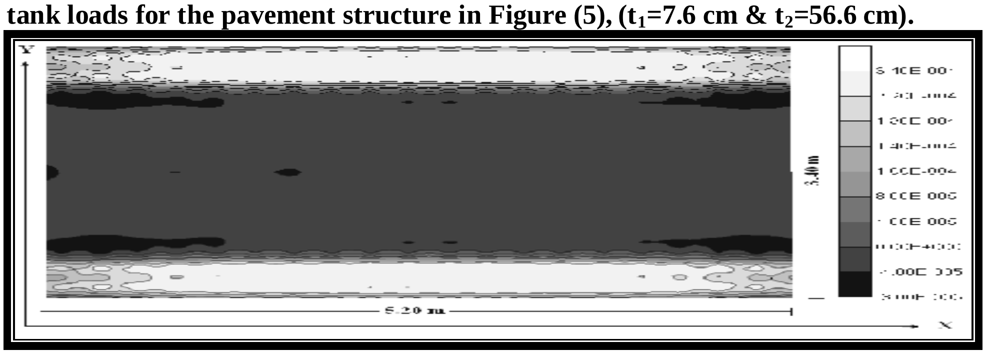


**Figure (11): Strains in the y direction at the surface of asphalt layer under the tank loads for the pavement structure in Figure (5), ($t_1$=7.6 cm & $t_2$=56.6 cm).**


**Figure (12): Strains in the z direction at the surface of asphalt layer under the tank loads for the pavement structure shown in Figure (5), ($t_1$=7.6 cm & $t_2$=56.6 cm).**

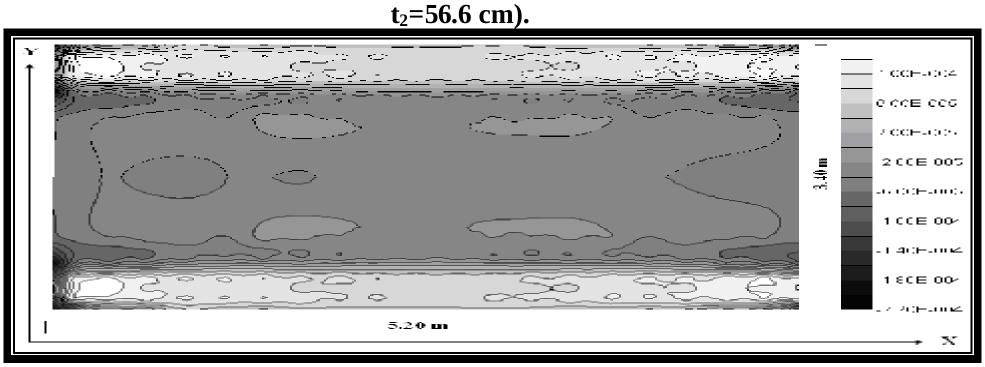


**Figure (13): Shear strain in the xy direction at the surface of asphalt layer under the tank loads for the pavement structure in Figure (5), ($t_1$=7.6 cm & $t_2$=56.6 cm).**