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DEPARTMENT OF CIVIL ENGINEERING

Increased Damage to Uphill Flexible Highway Pavement from Full-trailers

A Thesis Submitted to the
Department of Civil Engineering University of Kerbala
in Partial Fulfillment of the Requirements for
the Degree of Master of Science in
Civil Engineering (Infrastructure Engineering)

by
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October 2017 **Muharram 1438**

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

﴿ نَرْفَعُ دَرَجَاتٍ مَنْ نَشَاءُ وَفَوْقَ كُلِّ ذِي عِلْمٍ عَلِيمٌ ﴾

صدق الله العلي العظيم

سورة يوسف, الاية رقم (٧٦)

In the Name of Allah, the Merciful, the Most Merciful

﴿ *We raise in degrees whom we will, but over every possessor of knowledge is the all-knowing one* ﴾ ★

Great truth of God

Surah Yusuf, verse (76)

★ *Quran.com: Website to translate the Quran from Arabic to English language developed by* **Mohamed El-Mahallawy**.

DEDICATION

To

Prophet **Muhammad** (peace be upon him)

Human teacher and source of science, who guide the world to the light

My **mother**

A Strong and gentle soul who taught me to trust in Allah, believe in hard work and that so much could be done with little

My **father**

For earning and honest living for us and for supporting and encouraging me to believe in myself

My **sisters**

For their support me through words and actions

Researcher

Zahraa Hashim Al-hashimi

SUPERVISOR CERTIFICATION

We certify that this thesis entitled **"Increased Damage to Uphill Flexible Highway Pavement from Full-trailers"** which is prepared by **Zahraa Hashim Masha Allah Al-hashimi** under our supervision at the University of Karbala in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering (Infrastructure Engineering).

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CERTIFICATE OF THE EXAMINING COMMITTEE

We certify that we have read the thesis entitled **"Increased Damage to Uphill Flexible Highway Pavement from Full-trailers"** and as an examining committee, examined the student **Zahraa Hashim Masha Allah Al-hashimi** in its content and in what is connected with it, and that in our opinion it is adequate as a thesis for degree of the Master of Science in Civil Engineering (Infrastructure Engineering).

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ABSTRACT

The demand for transport has been growing rapidly and the footprints of roads have been widespread to areas which were previously inaccessible, especially mountainous areas. Road inclinations are not always at zero. Iraq, like the other countries in world, has different topographies where, there are different uphill pavements on ramps of interchanges and highways. On the other hand, AASHTO load equivalency factors are known for level pavements only. For this purpose, this study aims to determine the increase in damage to uphill flexible pavements from full-trailer trucks.

Presented in this thesis are a thorough field and theoretical study concerning the increased damage to uphill flexible pavements from six types of full-trailer trucks. An axle load survey covering 89 full-trailer truck with tandem front axle, has been carried out in this work using permanent weighing stations in Karbala and Hilla cities, gathered with available data for 254 trucks from surveys of previous researches. During the axle load survey, measurements of the wheelbase and other geometrical characteristics of each unit of each surveyed truck were made to obtain the proper range of the ratio of the height of the center of gravity to the corresponding wheelbase of the tractor unit and trailer unit of each surveyed full-trailer truck.

To determine the possible range of pavement uphill slope, an uphill slope survey was carried out on Ein Al-Tamur highway and several interchanges in Karbala city. In addition, some data of uphill slopes for several highways in Dohouk, Sulaimaniya and Erbil cities were obtained from previous surveys.

Due to axle loads redistribution on uphill pavements, the corresponding axle loads on rising grades were calculated, assuming uniform motion. This was achieved by taking the effects of the moment of the component of the weight parallel to the uphill slope and acting at the center of gravity of each unit of the full-trailer truck as well as of the pull force in the drawbar between tractor and trailer units.

For determining the AASHTO equivalency factors for the calculated axle loads on uphill flexible pavements, a computer program was written in Matlab named FEFUF (Full-trailer Equivalence Factor for Uphill Flexible pavements). Using this program, design charts of truck equivalence factors on uphill flexible pavements, having a rising grade of 0%, 6%, 12%, and 18%, were developed for each of the six types of full-trailer trucks under study. These design charts were developed for a terminal level of serviceability of 2.5, three values of a structural number of 2, 4, and 6 and five values of the ratio of the height of the center of gravity (H) to the wheelbase (B) of 0.2, 0.4, 0.6, 0.8, and 1.0. These design charts presented that the destructive effect of full-trailer trucks on uphill flexible pavements is greater than on level pavements for all values of structural number. This is especially true for full-trailer trucks with single rear axles on tractor and trailer units.

This thesis reveals the significant effects of pavement uphill gradient, type of full-trailer truck, structural number and of the H/B ratio on the truck equivalency factors. In addition, it reveals the significant increase in flexible pavement thickness with increasing uphill gradient especially for full-trailer truck type 11.2+2.2 and recommends the use of tandem rear axles for tractor and trailer units of full-trailer trucks to decrease the damaging effect of full-trailer trucks on uphill flexible pavements.

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LIST OF SYMBOLS

Symbols	Description
ΔPSI	Design serviceability loss
A	Frontal cross-sectional area, cm^2
a	acceleration
a_1, a_2, a_3	Structural coefficients of surface, base and subbase respectively
B_1	Wheelbase length of tractor of full-trailer, mm
B_2	Wheelbase length of trailer unit of full-trailer, mm
C	Class interval; Lineal feet of major cracking per 1000 ft^2 area
$c.g_1$	Center of gravity of the tractor unit
$c.g_2$	Center of gravity of the trailer unit
CD	aerodynamic drag coefficient
D_1, D_2, D_3	Thickness of surface, base and subbase in inches respectively, inch
d_{18}	Damage per pass of the standard vehicle (axle)
d_i	Damage per pass of the j^{th} vehicle (axle)
E	Height of the pull force above the pavement; maximum allowable error; empty full-trailer trucks
E_i	Equivalency factor for i^{th} axle
F_{G1}	Front axle load for a tractor on an uphill slope
F_{G2}	Front axle load for a trailer unit on an uphill slope
F_j	Axle load factor of a particular type of vehicle j
F_{L1}	Front axle load for tractor unit on a level road during uniform motion

F_{L2}	Front axle load for trailer unit on a level road during uniform motion
F_{O1}	Front axle load for tractor unit on a level surface
F_{O2}	Rear axle load for trailer unit on a level surface
g	Acceleration of gravity
G	Gradient
G_t	A function (logarithm) of the ratio in serviceability at time t to the potential loss taken to a point where p_t =1.5
H/B	The ratio height of center of gravity to the wheelbase of the truck
H_1	Height of center of gravity of the tractor unit above pavement, mm
h_1	Vertical distance measured from the top of the load container of tractor to the pavement, mm
H_2	Height of center of gravity of the trailer unit above pavement, mm
h_2	Vertical distance measured from the bottom of load container of the tractor to the pavement, mm
h_3	Vertical distance measured from the top of the load container of trailer unit to the pavement, mm
h_4	Vertical distance measured from the bottom of load container of the trailer unit to the pavement, mm
K	Type of full- trailer truck
L	Loaded truck
L_1	Load on one single-axle, one tandem-axle, or one triple axle set
l_{11}, l_{12}	Distances from center of gravity of tractor to its front and rear axles respectively, mm
L_2	Axle code (1 for single axle, 2 for tandem axle, and 3 for triple axle)
l_{21}, l_{22}	Distances from center of gravity of trailer unit to its front and rear axles respectively, mm

m_1, m_2	Drainage coefficients for surface and base layer
MR	Rupture modulus of concrete, psi
N	Sample size, number of observations data
n	Total number of full-trailer trucks, number of flexible pavement layers, total number of axles in the truck
N_{f18}	Number of repetitions to failure for the standard vehicle (axle)
N_{fj}	Number of repetitions to failure for the j^{th} vehicle (axle)
N_r	Required minimum sample size
P	Bituminous patching in ft^2 per 1000 ft^2 area
p_i	Initial serviceability index
p_t	Terminal serviceability index
R	Range between largest and smallest value
R	radius of curvature
Ra	air resistance force
R_c	curve resistance
R_g	grade resistance force
R_{G1}	Rear axle load for tractor on uphill slope
R_{G2}	Rear axle load for trailer unit on uphill slope
Ri	inertia resistance
R_{L1}	Rear axle loads for tractor unit on a level road during uniform motion
R_{L2}	Rear axle loads for trailer unit on a level road during uniform motion
R_{O1}	Rear axle load for tractor unit on a level surface
R_{O2}	Rear axle load for trailer unit on a level surface

R_r	rolling resistance force
s	Standard deviation of the sample
S.A	Single axle dual tired
S.A.S	Single axle single tired
S_{11}	Distance between the centers of the two axles of the front tandem axle in 11.2 and 11.22 tractor unit, mm
S_{12}	Clear distance between front and rear axles of the tractor unit type 11.2 and 11.22, mm
S_{13}	Distance between the centers of the two axles of a tandem rear axle of the tractor unit type 11.22, mm
S_{21}	Clear distance between front and rear axles of the trailer unit type 2.22, mm
S_{22}	Distance between the centers of the two axles of a tandem axle of the trailer unit
SN	Structural number
S_O	The combined standard error of the traffic prediction and performance prediction
T	Pull force between the tractor and the trailer unit on uphill slope
T.A	Tandem axle
T.A.S	Tandem axle single tired
T_a	Average truck equivalency factor
T_e	Truck equivalency factor
T_{ej}	Truck equivalency factor for j^{th} truck
T_O	Pull force between the tractor and the trailer unit on level road
u	vehicle speed
W	Gross weight of vehicle

W_1	Total weight of the tractor unit
W_1'	Weighing the tractor's axles together with the front axle of the trailer
W_{18}	Predicted number of 18 kips axle applications that can be carried by the pavement structure after construction
W_2	Total weight of the trailer unit, kN
W_t	Total weight of full-trailer truck
Z_R	Standard normal deviation corresponding to the selected level of reliability (r %)
β_{18}	Value of βj when l_1 is equal to 18 and l_2 is equal to 1
β_j	Shape function
θ	Slope angle
ρ	density of air at sea level
ΣESAL	Cumulative 18000-Ib (80 kN) equivalent single-axle loads

LIST OF ABBREVIATIONS

Abbreviations	Description
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
DTCFUF	Drawing Truck equivalency factor Charts for Full-trailer trucks on Uphill Flexible pavements
EALF	Equivalence Axle Load Factor
ESAL	Equivalent Single Axle Load
FEFUF	Full-trailer Equivalence Factor for Uphill Flexible pavements
HCM	Highway Capacity Manual
LEF	Load Equivalency Factors
OECD	Organisation for Economic Co-Operation and Development
PSI	Present Serviceability Index
PSR	Present Serviceability Rating
RD	Rut Depth
SCRB	State Commission for Roads and Bridges
SN	Structural Number
SORB	State Organization for Roads and Bridges
TEF	Truck Equivalence Factor
TRL	Transport Research Laboratory

1

CHAPTER ONE

INTRODUCTION

CHAPTER ONE

INTRODUCTION

1.1 General

As a result of the development all over the world after economic transformation in the early 1990s, road transport has rapidly grown. The vehicle class distribution has changed significantly, and trailer trucks became much more common (Rys et al., 2016).

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. Inspections indicate that overloading problem causes a large amount of damage to road networks and results in noticeable maintenance and repair costs (Maheri and Akbari, 1993).

Department of Transport, Pretoria (1997) showed that if the size and mass of a vehicle are not controlled, heavy loads may cause excessive damage to the road infrastructure. Road pavement structures are designed to carry a given number of standard axle load repetitions, and overloading reduces the design life of these structures.

Rolt (1981) pointed out that in many developing countries, vehicles are often loaded above the legal load limits. Not only the numbers of overloaded vehicles are large, but the magnitude of the overloading is high. Also this observed in some developed country such as China (Houben, 2005).

The pavement damage caused by any vehicle (axle) is usually identified by the equivalent axle load factor or load equivalency factor (Green and Morse, 1994; Lee and Garner, 1996).

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. The increase of damage to rigid uphill pavements of highways and ramps of interchanges with predominating full-trailer traffic 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 upgrade magnitude.

1.2 Commercial Vehicles Classification and Coding

Trucks are a major consumer of the pavement structure because they apply the highest loads to the road. Heavy trucks do not cause equal damage because of variations in wheel load (static and dynamic), number and location of axles, types of suspensions, the number of wheels, tire type and inflation pressure, and other factors (Gillespie et al., 1993).

Due to the high importance of commercial traffic in this study, commercial vehicles should be defined first and then classified into their major groups.

The term "truck" is used here to represent any vehicle whose primary mission is to transport cargo on highways. Thus, trucks include the single-unit vehicles known as straight trucks (also buses), multi-unit (articulated) vehicles covering the various combinations of tractor-semitrailers, doubles and triples, and trailers (Gillespie et al., 1993).Glover (1983) showed that the commercial vehicle as one having the unladen weight of 3.5 tonnes or more. Razouki et al. (1982) defined, for the axle load survey on Al-Kanat road in Baghdad, the commercial vehicle as one having an estimated unladen weight of about 6.0 tonnes or more. Wright et al. (1998) reflected the single–unit trucks as that having the power unit and cargo bed mounted on a common frame. These trucks range from vehicle massing of about 4536 kg and up to 18144 kg. According to TRB (2000), heavy vehicles are those having more than four tires touching the pavement. Garber and Hoel (2010) defined the heaviest trucks as those weighing over 11818.18 kg (26,000 Ibs), which are widely used in intercity freight; lighter ones transport goods and services for short distances.

The code used by Jones and Robinson (1976) to represent axle configuration is as follows:

Each vehicle is given an axle configuration code for ease of defining and processing the axle load data. This code is straight forward, and a digit of 1 and 2 represent each axle depending on how many wheels are on the end of the axle. Tandem axles are indicated by recording the digits directly after each other. A decimal point is placed between code digits for a vehicle’s front and back wheels. The codes for semi-trailers or articulated trailer are recorded in the same way as for trucks but is separated from the truck code by a minus sign. For the full-trailers, a plus sign is used.

Federal Highway Administration (FHWA), USA presented thirteen vehicle classes according to Transportation Research Board (2001). This classification system of vehicles is based on number of axles per vehicle and is exclusively used for collecting the traffic data needed for mechanistic empirical pavement design. This classification system was used in significant numbers in North America since 2000 and still in use.

Due to the importance of full-trailer in this work, the types of full trailers in common use in Iraq with their maximum gross weights according to State Commission for Roads and Bridges in Iraq ((SCRB), 2009), and their code numbers are shown in Table (1.1).The code used by Jones and Robinson (1976) for full-trailer is adopted throughout this thesis.

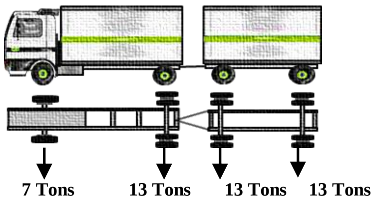
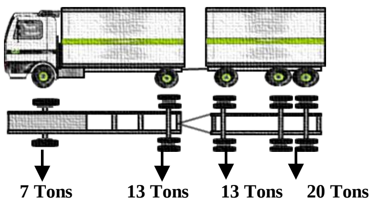
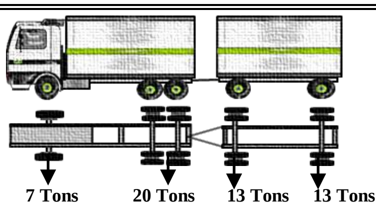
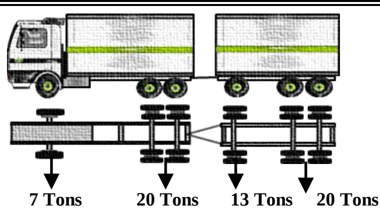
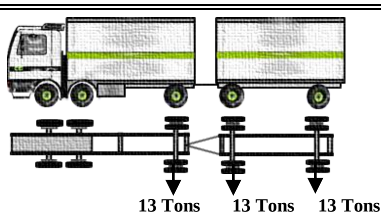
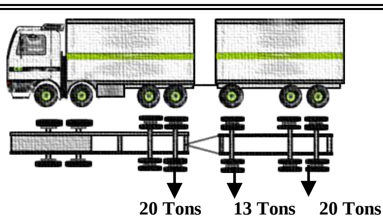
1.3 <u>Damaging Effect of Trucks</u>

Factors such as traffic, environment, materials, and design considerations affect pavement damage over time, with traffic loads are playing a key role in deterioration. Trucks are the major consumers of the pavement network, applying the heaviest loads to the pavement (Chatti et al., 2006).

Hutchinson (1990) showed that the damaging effects of different load magnitudes on different axle groups are normally defined in terms of a Load Equivalency Factor (LEF). The AASHTO factors obtained from analysis of the AASHO Road Test are the most popular equivalency factors (Yoder and Witczak, 1975).

The AASHTO equivalency factor defines the number of repetitions of the 18 kips standard single axle load that causes the same damage like that caused by one pass of the axle in question moving on the same pavement under the same conditions (AASHTO, 2001).

Table (1.1) Full-trailer characteristics, maximum gross weight, and their code number (after SCRB, 2009).

Full-trailer characteristics	Code numbers*	Vehicle type	Maximum gross weight (Tons)
	1.2+2.2	type 2-2	46
	1.2+2.22	type 2-3	53
	1.22+2.2	type 3-2	53
	1.22+2.22	type 3-3	60
	11.2+2.2	-----**	-----**
	11.22+2.22	-----**	-----**

*****Code numbers or vehicle types (afterJones and Robinson, 1976).
**Don't have coding according to State Commission for Roads and Bridges in Iraq ((SCRB), 2009).

The wheel loads of heavy trucks contribute to various forms of pavement distress including fatigue (which leads to cracking) and permanent deformation (rutting). However, not all trucks have the same damaging effects. The damage to the road pavement depends on speed, wheel loads, number and location of axles, load distributions, type of suspension, the number of wheels, tire types, inflation pressure and other factors (Gillespie et al., 1993).

The damage to roadway pavement caused by passenger cars is very limited compared with that caused by trucks. Therefore, pavements are designed to support a specified number of heavy vehicle loadings over their design life (Newnan, 1998).

The axle load is a much stronger determinant of pavement damage than is gross vehicle weight. On the basis of European road test, estimates are presented for the exponent in the exponential relationship posited between pavement damage and axle load (a relationship termed the "load equivalence law"). For flexible pavements generally, an exponent of about (4), the same as in the AASHTO based forth power law was considered a reasonable value (Organisation for Economic Co-operation and Development (OECD), 1988).

1.4 Aimof the Study

The main aim of this research is to study the increase in damage of full-trailer traffic on uphill flexible pavements. Also to investigate the effect of uphill slope on the design of flexible pavements. To achieve this goal, the following objectives are to be determined:

1. Updating of the axle load data gathered from a previous study will be necessary, and this will be accomplished by carrying out a proper axle load survey in Karbala and Hilla cities.
2. Updating of the range of uphill slopes magnitude to represent the uphill slopes range in Iraq, and this will be accomplished by carrying out a proper uphill slope survey for the ramps of interchanges and highways in Karbala city.
3. Simplifying the design process for pavement designers, design charts as well as MATLAB program, will be developed for the quick determination of the corresponding truck equivalence factor for all possible uphill flexible pavements slopes.
4. Introducing the effect of uphill slope on the design of flexible pavement.

1.5 Outline of the Study

The general procedure adopted in this thesis for determining the increase in the destructive effect of full-trailer trucks on flexible uphill highway pavements design is given through six chapters as follows:

1. Chapter one gives an idea about the definition of the destructive effect of trucks on level pavements and its increase on uphill pavements due to axle load redistribution on uphill slopes. Also demonstrates the main aim and objectives of the study.
2. Chapter two is devoted to the literature review concerning the damaging effect of trucks with a special reference to full trailer trucks on uphill pavements with different rising grades.

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3. Chapter three is dedicated to the collection and analysis of geometrical and structural data required to obtain the actual range of each parameter involved in the determination of the destructive effect of full trailer trucks on uphill flexible pavements.

4. Chapter four deals with the analysis of forces for full-trailer trucks on uphill slopes and the determination of the corresponding truck equivalence factor.

5. Chapter five is devoted to the design charts for equivalence factors of full-trailer trucks on uphill flexible pavements taking into account pavement structural number, the terminal level of serviceability, the magnitude of the uphill slope, and the relative height of the center of gravity of each unit of the full-trailer. This chapter deals also with the application of the developed factors on a road pavement with specialized traffic to show the significant effect of uphill gradient on the increase in flexible pavement thickness.

6. Chapter six is devoted to the conclusions and recommendations drawn from this work.

2

CHAPTER TWO

LITERATURE REVIEW

CHAPTER TWO

LITERATURE REVIEW

2.1 General

In order to achieve the goal of this thesis, it is necessary first of all to review all factors affecting the destructive effects of trucks on uphill flexible pavements. Such factors include, among others, the pavement components and materials, geometric characteristic of full-trailers of interest, the phenomenon of overloading, the terminal level of serviceability, maximum limits for uphill slopes and the AASHTO load equivalency factors.

2.2 Flexible Pavement Components and Materials

Generally, road pavements can be classified into two types: flexible and rigid pavements. The former are the most widely used transportation infrastructures all around the world.

Wright et al. (1998) showed that a flexible pavement is composed of a series of granular layers topped by a relatively thin high-quality bituminous wearing surface. Adherence to this design principle makes possible the use of local materials and usually results in a most economical design (Huang, 2004).

The various layers comprising a flexible pavement are described below (Huang, 2004; Garber and Hoel, 2010; Wang, 2011):

Subgrade (prepared roadbed) is usually the natural material located along the horizontal alignment of the pavement and is seldom strong enough to support the load application alone. Garber and Hoel (2010) and AASHTO (1993) pointed out that the resilient modulus (M_R) is a measure of the strength of the subgrade, which gives the resilient characteristic of the soil when it is repeatedly loaded with an axle load.

Subbase course located immediately above the subgrade. This layer is used in areas where frost action is severe or in locations where the subgrade soil is extremely weak and consists of a higher-quality soil material than that for the subgrade. The subbase works in conjunction with the base to support the wheel loads and also provides resistance to the flexure of the base layer.

Base course is the principal structural component and usually consists of granular materials such as crushed stone, crushed or uncrushed slag, crushed or uncrushed gravel, and sand. The base gives the pavement most of its strength and has a relatively large thickness.

Surface course is the upper course of the road pavement. The surface course usually consists of a mixture of mineral aggregates and asphalt materials, with or without additives. The surfacing is usually of high quality, tough enough to withstand direct loading and to provide good ride quality.

The AASHTO-Guide (AASHTO, 1993) showed that the structural strength of a flexible pavement is expressed by an abstract number called the structural number (SN). The SN is derived from subgrade soil condition and regional factors that may be converted to a thickness of various flexible pavement layers. This is achieved using appropriate layer coefficients (a_i) representing the relative strength of the construction materials and drainage coefficient (m_i).The structural number is computed as follows:

$$SN = a_1 D_1 m_1 + a_2 D_2 m_2 + a_3 D_3 m_3$$

or

$$SN = \sum_{i=1}^{n} a_i D_i m_i \quad (2.1)$$

where:

a_i= i^{th} layer coefficient.

D_i=i^{th} layer thickness (inches).

m_i=drainage coefficient for the i^{th} layer.

n=number of layers.

Huang (2004) defined the layer coefficient (a_i) as the measure of the relative ability of a unit thickness of a given material to function as a structural component of the pavement.The layer coefficients can be determined from correlations with material properties. However, AASHTO Guide (AASHTO, 1993) recommended that the layer coefficients should preferably be based on the resilient modulus that is a more fundamental property.Figures (2.1) and (2.2) show the correlation of layer coefficient to material properties.

The drainage coefficient (m_i) is based on the quality of the drainage and the percentage of time during which the pavement structure will be nearly saturated (Garber and Hoel, 2010).This drainage coefficient should be applied to granular bases and subbases to modify the layer coefficients (Huang, 2004).

Table (2.1) shows that the quality of drainage is measured by the length of time for water to be removed from base or subbase layer and this depends on the permeability.

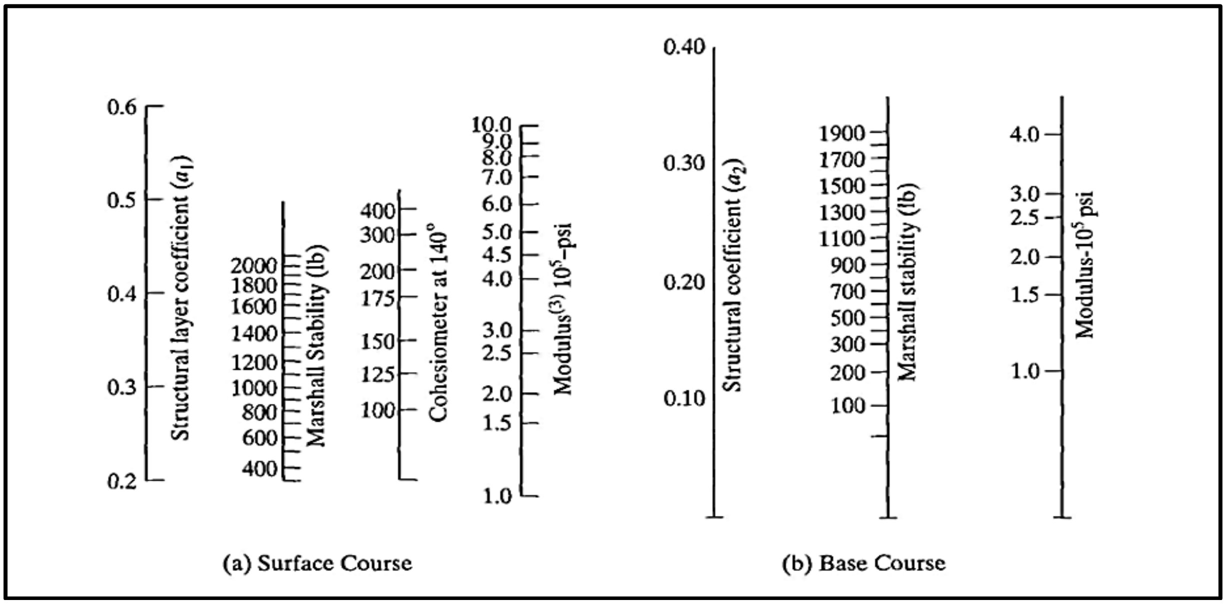


Fig.(2.1) Correlation charts for estimating the layer coefficients a_1 and a_2 from resilient modulus (after AASHTO, 1993).

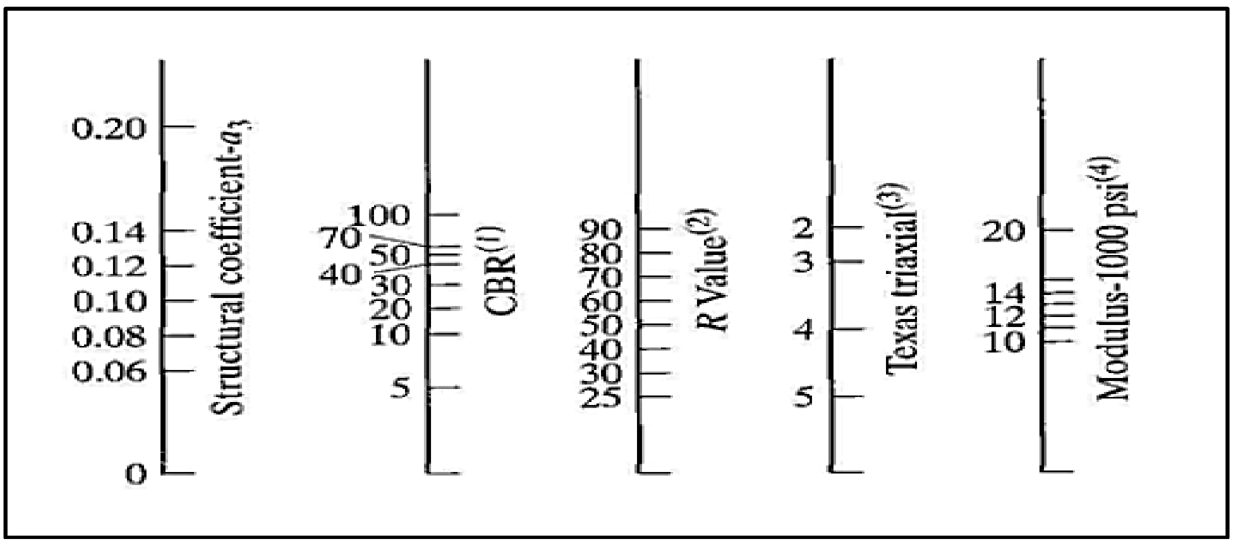


Fig.(2.2) Correlation chart for estimating the layer coefficient a_3 from resilient modulus (after AASHTO, 1993).

The time during which the pavement structure is exposed to moisture levels approaching saturation depends on the average yearly rainfall and the prevailing drainage conditions.

Table (2.1) Recommended drainage coefficients of untreated base and subbase materials in flexible pavements (After Huang, 2004).

Quality of drainage	Percent of time pavement structure is exposed to moisture levels approaching saturation			
	Less than 1%	1-5%	5-25%	Greater than 25%
Excellent	1.40-1.35	1.35-1.30	1.30-1.20	1.20
Good	1.35-1.25	1.25-1.15	1.15-1.00	1.00
Fair	1.25-1.15	1.15-1.05	1.00-0.80	0.80
Poor	1.15-1.05	1.05-0.80	0.80-0.60	0.60
Very poor	1.05-0.95	0.95-0.75	0.75-0.40	0.40

Lee and Garner (1996) reported that the structural number at AASHO Road Test ranged from 1to 6 since structural number greater than 6 did not noticeably change the results of the calculated equivalence factors.

2.3 Geometrical Characteristicsof Full-Trailers

There are many highway infrastructure design criteria that need to be in the light of recent evidence on behavior and properties of trucks.

The full-trailer trucks are still the most type of trucks in use for transportation of goods on Iraqi highway network. This fact was supported by Al-Muhanna (2008) who carried out an axle load survey on highways leading to grain silos and construction materials sources in Karbala city.He also reported that 55% of the trucks carrying grains were full-trailers. This fact encouraged the development of this research work.The full-trailer is a trailer that is pulled by a drawbar attached to the preceding unit, but the drawbar transfers no weight to the preceding unit (Harwood, 2003).

Razouki and Al-Muhanna (2010) pointed out that the height of drawbar above the pavement surface (E) affects the moment value (moment of drawbar pull above the pavement) for both the tractor and the trailer. It was found that in 87% of full-trailer trucks,the elevations of both ends of the drawbar, were 100 cm above the pavement.

The height of the center of gravity is the most important geometrical characters of commercial vehicles (Razouki and Mohee, 1999). The wheelbase is the distance between the centers of the front and rear axles of each unit of the full-trailer.The height ofthe center of gravity of the tractor unit is H_1 and of the trailer unit is H_2, while the wheel base B_1belongs to the tractor unit and B_2 to the trailer unit as shown in Figure (2.3).

Yang (2005) pointed out that the vehicle center of gravity height is one of the most important factors affecting vehicle roll stability. It varies considerably with the loading practices and the nature of cargo.

For loaded single unit Scania truck, Negus (2000) estimated the height of center of gravity to be about 3.12 m above the pavement.

Lenker (1977) reported that the height of the center of gravity and the wheelbase for a loaded single unit truck he studied, are about 1.66 m and 4.5 m respectively.

Razouki and Radeef (2005) reported that the wheelbase for truck type 1.2 (a truck with a single front axle with a single tire on each end and dual tired single rear axle), varied from 3.35 to 5.5 m and the height of the center of gravity varied from 1.3 to 3.4 m.

However, for truck type 1.22 (truck with dual tired rear tandem axle), the wheelbase varied from 3.90 to 6.145 m, and the height of the center of gravity ranged from 1.32 to 3.95 m. The ratio of the height of the center of gravity (H) to the wheelbase (B) of the truck was in the range of 0.3 to 1.0 (Razouki and Radeef, 2005).

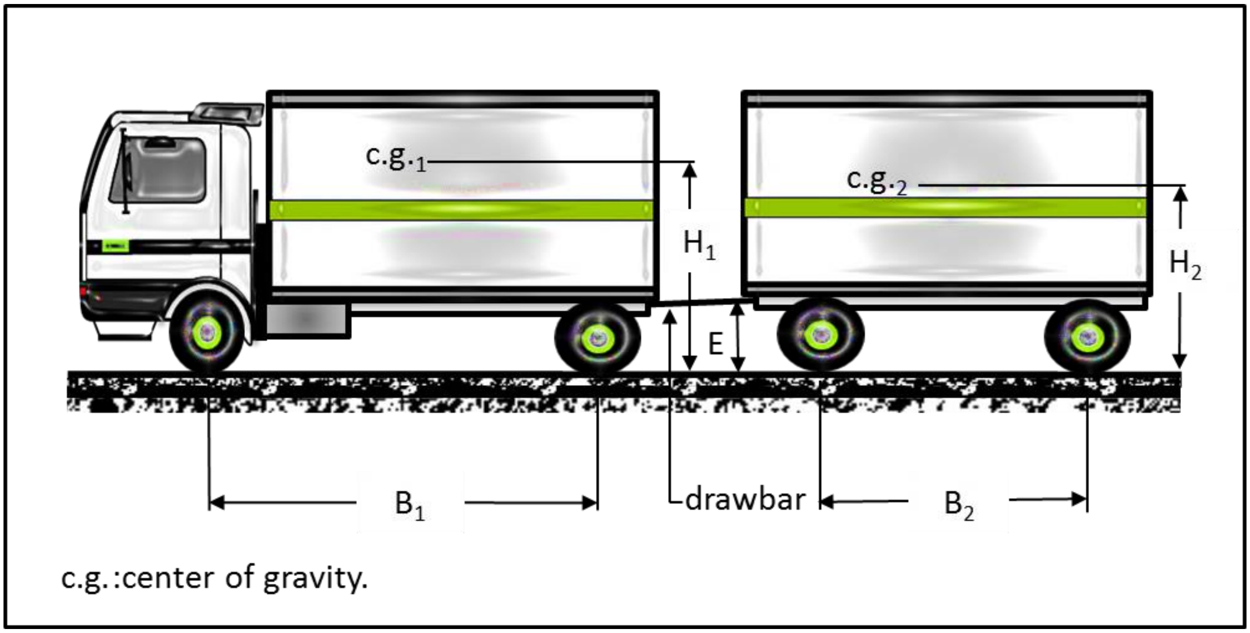


Fig. (2.3) Geometrical characteristics of full-trailers.

For the case of full-trailers, Razouki and Al-Muhanna (2010) pointed out that the wheelbase for the tractor unit type 1.2 varied from 3.35 to 5.5 m and the height of the center of gravity varied from 1.24 to 3 m, while for tractor unit type 1.22 the wheelbase varied from 3.91 to 6.1 m and the height of the center of gravity varied from 1.3 to 3.95m. The wheelbase andthe height of center of gravity for trailer unit type 2.2 varied from 4.9 to 5.78 m and 1.23 to 2.95m respectively, while for trailer unit type 2.22 varied from 3.92 to 4.75 m and 1.65 to 3.3 m respectively. The ratio of (H/B) was in the range of (0.35 to 1.0).

2.4 <u>Phenomenon of Overloading</u>

Legesse (2013) pointed out that the growing demand for the transportation more than ever, calls for an effective transport system. This associated by introducing heavy trucks and trailers truck to transport goods. Although this is a natural trend of economic growth, the damage resulting from these commercial vehicles on the asphalt surface layer of flexible roads was intense by the excessive increase in axle load that exceeds the limits permitted. These limits reflect the different environmental and social conditions of each country, but economic analyses have rarely, if ever, been used to justify them (Team, 1995). Tseng et al. (2005) showed that increasing axle load limits will aid the logistic industry by decreasing the number of trips needed to transport certain volume of goods.

Overloading truck traffic is an untenable problem around the world. This phenomenon in developing countries is more serious than developed ones as enforcement and inspection are not as effective (Chan, 2008).Indeveloped countries such as U.S. Taylor et al. (2000) showed that the level of the overloaded vehicle U.S. interstateswas about 20–30% when there was no enforcement, while high enforcement decreased the level of the overloaded vehicle to be under 2%. The application of effective enforcement system can reduce the percentage of overloading vehicles, which can achieve the design life of the pavement. Rys et al. (2016) reported that a decrease of percentage in overloaded vehicles by 10% might cause an increase in the service life in the pavement from 4 to 6 years.

Fekpe and Oduro-Konadu (1993) pointed out that the impact of the high incidence of heavy vehicle overloading is assessed by the increase in damage level in terms of the equivalent single axle load (ESAL)and reduction in pavement life in terms of the combined effects of overloading and violation rates. Rys et al. (2016) reported that the increase of the percentage of overloaded vehicles from 0% to 20% could reduce the fatigue life of asphalt pavement in a range of 50%.

The occurrence of overloading truck traffic induces incorrect estimation in total ESALs, which corrupts the frequency of maintenance and rehabilitation within the service (Chan, 2008). Pais et al. (2013) reported that maintenance cost of road calculated per one vehicle is higher by 100% for overloaded vehicles compared to the cost of the same vehicle with legal loads.

Chan (2008) pointed out that the net present value of total pavement investment increased by 105% when the pavement services life reduced by 26% due to the overloading of vehicles.

Most of the overloaded vehicles exceed their axle load limit, whereas the gross weight is exceeded less frequently (Rys et al., 2016).The axle load surveys of commercial vehicles carried out in many Arab countries (such as Iraq, United Arab Emirates, Qatar, Kuwait, etc.) have shown excessive overloading (Razouki, 1992).

Razouki et al. (1982) pointed out that the maximum single and tandem axle loads for commercial vehicles observed on Al-Kanat road in Baghdad were about 22 and 34 tonnes (215.75and 333.43 kN), respectively. The corresponding maximum allowable axle loads limits were 11 and 17 tonnes (107.87 and 116.71-kN), respectively. Al-Shefi (1997) showed that the maximum observed axle loads for single unit trucks on Baghdad roads were 11.78, 23.2 and 37.4 tonnes (115.56, 227.59 and 336.89kN) for front single, rear single and rear tandem axles, respectively. Mohee (1992) reported that on Baghdad roads, the observed maximum front single, rear single and rear tandem axle load for single unit trucks were 11, 30 and 49 tonnes (107.91, 294.30 and 480.69 kN), respectively. The corresponding allowable axle loads limits were 6, 12 and 20 tonnes (58.84, 117.72, and 176.58 kN) for front single, rear single and rear tandem axles respectively (State Commission for Roads and Bridges in Iraq SCRB, 1993).

Razouki and Abo-shaeer (1997) reported that 90% of all loaded heavy commercial vehicles in Iraq showed overloading. The amount of overload was 200-300 percent times the legal limits. The maximum observed axle loads for single unit trucks obtained from the axle load survey carried out by Razoukiand Radeef (2002) in Baghdad were 12.48, 27.8, and 31.58 tonnes (122.43, 272.72, and 309.80 kN) for front axle, single rear and rear tandem axles, respectively. The corresponding limits were 6, 12 and 20 tonnes (58.84, 117.72, and 176.58 kN) for front single, rear single and rear tandem axles, respectively (SCRB, 1993). The axle load survey for full-trailer trucks carried out by Al-Muhanna (2008) in Karbala, Baghdad and Hilla silo showed that the maximum axle loads were 12.32, 28.32, and 34.58 tonnes (120.32, 277.819, and 339.229 kN) for the front axle, single rear and rear tandem axles respectively. The corresponding axle load legal limits were 6, 10 and 18 tonnes (58.84, 98.07 and 176.52kN) for front, rear single and rear tandem axle load respectively (SCRB, 2005).

The maximum observed axle loads in Iraq and other countries in the world are shown in Table (2.2) (Razouki, 1992).

Table (2.2) Maximum observed axle loads in different countries (afterRazouki, 1992).

Country	Maximum axle loads (tonne)			
	Single axle	Tandem axle	floating tandem axle	triple axle
Iraq	22.0	34.0	26.13	45.5
United Arab Emirates	20.0	33.9	------	------
Qatar	20.0	38.3	------	------
Sultanate of Oman	18.6	31.7	------	------
Kuwait	14.0	20.0	------	------

Karim et al.(2013) reported that the axle load survey carried out in Malaysia during 2010 showed that 50% of the 3-axle trucks were overloaded and the degree of overloading reached 101%.More than a third of the 4-axle trucks (37%) were also overloaded, and the degree of overloading reached 84% of the legal weight limit. As such, the 3-axle and 4-axle trucks may be considered as the main contributors to truck overloading occurrences in Malaysia. Furthermore, even though only 9% of the 2-axle trucks were overloaded, the degree of overloading ranged up to 120%.

Osman et al. (2009) stated that the increased axle loads limits by 17-36%, cause increases in the truck equivalence factor (TEF) by about 200%. The TEF was used to determine the ESAL needed for pavement design and maintenance works. This increase in TEF caused an increase in ESALs by 75-136%. This impact was converted into additional thickness of asphalt layers, which ranged from 2.1 to 4.6 cm depending on restrictions on overloading and scenarios of freight volumes.

To protect the road infrastructure, it is necessary to ensure that the forces exerted by vehicles on the road infrastructure do not exceed the permitted axle load limits and not in excess of what the road infrastructure was designed for (Beyene, 2015).

2.5 Terminal Level of Serviceability

Serviceability is the ability of a specific section of pavement to serve traffic in its existing condition. The present serviceability index (PSI) is one of the methods used to determine the serviceability, which was developed during the AASHO road test for correlating user opinion with measurements of road roughness, and distress condition such as rutting, cracking, and patching as shown in the following equation (AASHTO, 1993 and Huang, 2004).

$$\mathbf{PSI = 5.03 - 1.91\ Log\ (1 + SV) - 0.01\sqrt{C + P} - 1.38\ \overline{RD}^2} \qquad \mathbf{(2.2)}$$

where :

PSI = Present Serviceability Index.

SV = Mean slope variance, a measure of the unevenness of the pavement.

C = Lineal feet of major cracking per 1000 ft^2 area.

P = Bituminous patching in ft^2 per 1000 ft^2 area.

$\overline{\mathbf{RD}}$ = Rut Depth in inches (both wheel tracks) measured with a 4 ft straightedge.

Yoder and Witczak (1975) showed that the present serviceability index is determined by a panel of individuals. This panel rates the pavement on a rating scale from 0 through 5. A value of 5 indicates an excellent pavement, while a value of zero indicates impassable pavement. The average rating obtained for each road was called the “present serviceability rating” (PSR).Yoder and Witczak (1975) pointed out that the number of raters required depending on the permissible error and the probability level so that for a permissible error of 0.5 and a probability level of 0.05, eleven raters are required.

There are two values of PSI necessary for design purposes, initial and terminal serviceability index p_i and p_t respectively. The value of $p_i$representingPSI immediately after construction,while $p_t$valuerepresents the lowest accepted level of serviceability before resurfacing or reconstruction. The AASHTO (1993) recommends a value of 3.0, 2.5 and 2.0 for the terminal level of serviceability $p_t$for freeways and expressways, major highways, and minor roads and streets respectively.

AASHTO (1993) pointed out that the major factors affecting the loss of serviceability of pavement are traffic, age, and environment.

2.6 <u>Uphill Slopes</u>

Before reviewing the current grades on uphill pavements of highways and ramps of interchanges in Iraq, it is worth mentioning that the maximum slope currently permitted by various standards is dependent on the design speed and type of terrain. In mountainous terrain, AASHTO-policy (AASHTO, 2017) recommends the maximum grade for urban and rural freeways for design speeds of 60 and 70 mphto be 6% and 5%, respectively. For local roads and streets, AASHTO's values for maximum grades are considerably higher. However, for a design speed of 50 km/h (approximately 31 mph) the maximum grade ranges from 7% to 12% depending on the topography. For short grades less than 150 m [500 ft] in length and for one-way downgrades, the maximum grade may be about 1 percent steeper than other locations; for low-volume rural highways, the maximum grade may be 2 percent steeper (AASHTO, 2017).

In Iraq, Razouki and Radeef (2005) showed that the existing maximum grade for ramps of interchanges in Baghdad was 7%. However, Razouki and Al-Muhanna (2010) reported that the measured maximum grade for some highways in the north of Iraq (Dohouk, Sulaimaniyaand Erbil) was 18%. Thus, for the purpose of this work, the range of grade from 0 to 18% was considered suitable to represent uphill slopes in Iraq.

2.7 <u>Resistances of Truck during Motion</u>

Several forces act on a vehicle while it is in motion, such as air resistance, grade resistance, inertia resistance, rolling resistance, curve resistance, and friction resistance. This is the resistance a vehicle faces while attempting to move from a stall condition or while accelerating. This resistance must be overcome by the power plant of the engine in order to sustain motion. When the power produced is smaller than the resistance to motion, the vehicles will gradually slowdown. These forces affect the operation of the vehicle (Garber and Hoel, 2010).

2.7.1 Air Resistance

A vehicle in motion has to overcome the resistance of the air in front of it as well as the force due to the frictional action of the air around it. The force required to overcome these is known as the air resistance and is related to the cross-sectional area of the vehicle in a direction perpendicular to the direction of motion and to the square of the speed of the vehicle (Garber and Hoel, 2010). This force can be estimated from the following equation (Harwood, 2003):

$$\mathbf{Ra = 0.5\frac{(2.15 * \rho * C_D * A * u^2)}{g}} \qquad \mathbf{(2.3)}$$

where:

Ra =air resistance force (Ib).

ρ = density of air (0.00238 Ib/ft^3) at sea level; less at higher elevation.

C_D = aerodynamic drag coefficient (current average value for passenger cars is 0.4; for trucks, this value ranges from 0.5 to 0.8, but a typical value is 0.5).

A = frontal cross-sectional area (ft^2).

u = vehicle speed (mph).

g = acceleration of gravity (32.2 ft/sec^2).

2.7.2 Grade Resistance

When the vehicle moves on uphill, a component of its weight works in a direction opposite to its motion. This force is the grade resistance. If some energy is not supplied to overcome this backward force, then the vehicle would slow down, stall and roll backwards (Garber and Hoel, 2010).

Khisty and Lall (2006) define grade resistance force (R_g) as follows:

$$\mathbf{R_g = W \cdot Sin\theta \cong W \cdot tan\theta = \frac{W \cdot G}{100}} \quad \textbf{(2.4)}$$

where:

$\mathbf{R_g}$ = Grade resistance force (Ib).

W = Gross weight of vehicle (Ib).

θ = Slope angle (degrees).

G = Gradient (%).

Wright (1996) reported that steeper grades (up to a reasonable maximum) are permissible on highways, but the speed of loaded trucks is greatly reduced. Thus, efficiency and capacity of two-lane highways may be increased by providing added climbing lanes on upgrade where critical lengths of grade are exceeded or by providing more frequent and longer sections safe for passing.

TRB (2000) defines the climbing lane as a passing lane added on an upgrade to allow traffic to pass heavy vehicles whose speeds are reduced.

2.7.3 Rolling Resistance

On motion, there are forces within the vehicle itself that offer resistance to motion. These forces are due mainly to frictional effect on moving parts of the vehicle, but they also include the frictional slip between the pavement surface and the tires (Garber and Hoel, 2002).Rolling resistance is a general term used to describe the resistance to motion at the area of contact between a vehicle's tires and the roadway surface and is only applicable when a vehicle is in motion (AASHTO, 1993).The rolling resistance depends on the speed of the vehicle and the type of pavement (Wright, 1996).

For trucks, the rolling resistance can be obtained as follows (Garber and Hoel, 2010):

$$\mathbf{R_r = (C_a + 1.47C_b * u)\ W} \qquad \textbf{(2.5)}$$

where:

$\mathbf{R_r}$ = rolling resistance force (Ib).
$\mathbf{C_a}$ = constant (typically 0.2445 for trucks).
$\mathbf{C_b}$ = constant (typically 0.00044 sec/ft for trucks).
u = vehicle speed (mph).
W = gross vehicle weight (Ib).

2.7.4 Curve Resistance

When a vehicle is maneuvered to take a curve, external forces act on the front wheels of the vehicle. These forces have components that have a retarding effect on the forward motion of the vehicle. The sum effect of these components constitutes the curve resistance. It can be determined as follows (Garber and Hoel, 2010):

$$\mathbf{R_c = 0.5\frac{(2.15u^2W)}{g\,R}} \qquad \textbf{(2.6)}$$

where

$\mathbf{R_c}$ = curve resistance (Ib).
u = vehicle speed (mph).
W = gross vehicle weight (Ib).
g = acceleration of gravity (32.2 ft/sec^2).
R = radius of curvature (ft).

2.8 AASHTO Load Equivalency Factor

The AASHTO method of pavement design is an empirical method that relates pavement performance, traffic loading and volume characteristic, characteristics of pavement material, and environmental factors. The main objective of the AASHTO design method is to determine a flexible pavement thickness that is expressed in terms of a structural number (SN), which is adequate to carry the design equivalent single axle load (ESAL) repetitions.

As mentioned before, the traffic load has the most important impact on the pavement. It depends on the characteristics of the vehicle, especially the number of axles, axle loads, axle configuration, and other factors (U.S. Department of Transportation (USDOT), 2000). The effect of the traffic load may be expressed in a single index called the “equivalent single axle load factor (EALF)”.Yoder and Witczak (1975) reported that the most popular equivalency factors are the AASHTO factors obtained from Liddle’s analysis of the AASHO Road Test.

EALF is defined as a standard term that converts the effect of mixed axle load applications into the equivalent number of applications of an 18kip (80kN) single axle that would be required to produce the same amount of pavement distress (Hutchinson, 1990).The most popular standard axle is the American Association of State Highway and Transportation Officials (AASHTO) 18 kips (80 kN) single axle with dual tires on each end (Yoder and Witczak, 1975). In Iraq, the 18kip (80kN) standard single axle with dual tires is widely used (State Organization for Roads and Bridges (SORB), 1983; State Commission for Roads and Bridges (SCRB), 2003).

For flexible pavements, the AASHTO equivalent factors depend on axle type, axle load, structural number (SN) and terminal level of serviceability (p_t) (Huang, 2004).

Yoder and Witczak (1975) showed that the EALF is a ratio relating the damage caused by a passing of an axle to the damage caused by an 18kips single axle load as shown in the following equation:

$$\mathbf{EALF = d_i / d_{18} = (1/N_{fi}) \,/\, (1/N_{f18}) = N_{f18}/N_{fi}} \qquad \mathbf{(2.7)}$$

where:

$\mathbf{d_i}$=damage caused by i[th] vehicle (axle).

$\mathbf{d_{18}}$= damage caused by 18-kips single axle load.

$\mathbf{N_{fi}}$= number of repetitions to failure for the (i[th]) axle.

$\mathbf{N_{f18}}$= number of repetitions to failure for the standard axle.

For flexible pavements, the AASHTO (1993) recommends the following equation for EALF:

$$\mathbf{E_i = \frac{Nf_{18}}{Nfi} = \left[\frac{L_1 + L_2}{(18+1)}\right]^{4.79} \cdot \left[\frac{10^{\left(G_i/\beta_{18}\right)}}{10^{\left(G_i/\beta i\right)} . L_2^{\;4.33}}\right]} \qquad \mathbf{(2.8)}$$

where:

$$\mathbf{G_i = \log_{10}\left(\frac{4.2 - p_t}{4.2 - 1.5}\right)} \qquad \mathbf{(2.8a)}$$

$$\mathbf{\beta_i = 0.40 + \frac{0.081 * (L_1 + L_2)^{3.23}}{(SN+1)^{5.19} * L_2^{\;3.23}}} \qquad \mathbf{(2.8b)}$$

where:

$\mathbf{E_i}$=equivalency factor.

$\boldsymbol{\beta_{18}}$ = value of β_i when L_1 is equal to 18-kips and L_2 is equal to 1.

$\mathbf{p_t}$=terminal serviceability.

L_1 = load on one single-axle, one tandem-axle, or one triple axle set (kips, 1kip = 4.448 kN).

L_2= axle code (1 for single axle, 2 for tandem axle, and 3 for triple axle).

SN = structural number for flexible pavements.

The summation of load equivalency factors for the front and rear axle loads of a particular vehicle is termed the truck equivalency factor according to AASHTO (1993), which can be calculated as follows.

$$\mathbf{Te} = \sum_{i=1}^{n} \mathbf{E_i} \qquad \textbf{(2.9)}$$

where:

T_e= truck equivalency factor.

E_i= equivalency factor for the i^{th}axle.

n= total number of axles in the truck.

Newnan and Banks (2004) has shown that the truck equivalence factor for the passenger car is about 0.0008, while for a heavy truck, on the other hand, approaches 2.4 when loaded to the legal limit and can be as high as 10 for overloaded trucks.

However, all previous studies carried out for calculating the truck equivalency factors were devoted to level highways, except those carried out by Razouki and Mohee (1999), Razouki and Radeef (2005) and Razouki and Al-Muhanna (2010),which were devoted to a wide range of uphill slopes as it will be shown in the next section.

2.9 Effect of Uphill Slope on Truck Equivalency Factor

The damaging effect (equivalency factor) of vehicles moving on pavements is different on the uphill slope than on level highways. The uphill slope causes a redistribution of axle loads, due to the moment introduced by the component of the weight parallel to the road surface. This moment increases as the height of the center of gravity of truck above the road surface increases.

For a single-unit truck, Razouki and Mohee (1999) pointed out that the amount of increase and decrease in the rear and front axle load respectively increases with the increase of uphill slope and H/B ratio (the ratio of the height of the center of gravity to the wheelbase of the truck).

As mentioned in chapter one, Razouki and Mohee (1999), Razouki and Radeef (2005) and Razouki and Al-Muhanna (2010) reported that, for a truck unit, the increase in the rear axle load is the same as the decrease in front axle load, but the increase in damaging effect of the rear axle load is much greater than the decrease in the damaging effect of the front axle load. This is due to the fact that the damaging effect is a highly non-linear function of axle load magnitude (Lin et al., 1996).

For flexible pavements, the average truck equivalency factor for single unit trucks type 1.2 was 75.17 corresponding to SN=1, H/B =1.0, p_t =2 and uphill slope of 13%, while the corresponding average truck equivalency factor was 36.17 for uphill slope of 0% (level highways) (Razouki and Radeef, 2005). For rigid pavements, Razouki and Al-Muhanna (2010) pointed out that the average truck equivalency factor for full-trailer type 1.2+2.2 was 107.32 for a slab thickness (D) =14 inches (35.6 cm), H/B =1.0, p_t=2.5 and uphill slope of 18%, while the corresponding average truck equivalency factor was 41.17 for uphill slope of 0% (level highways).

Regarding the effect of H/B ratio, Razouki and Radeef (2005) reported that for single-unit trucks of type 1.2 on a flexible pavement with SN=1, uphill slope of 13% and p_t =2, the average truck equivalency factor was 40.78, for H/B ratio of 0.2 and 75.17 for H/B=1.0. For full-trailer trucks of type 1.2+2.2 on rigid pavements, D=14 inches (35.6cm), uphill slope of 18% and p_t =2.5, Razouki and Al-Muhanna (2010) reported an average truck equivalency factor of 53.69 for H/B of 0.2 and 107.32 for H/B =1.0.

For flexible pavements, Razouki and Radeef (2005) pointed out that the truck equivalency factor for a single-unit truck on uphill slope decreases with increasing the magnitude of the structural number and terminal level of serviceability.For single-unit trucks of type 1.2 and H/B=1.0, p_t =2 and uphill slope of 13%, Razouki and Radeef (2005) reported a decrease of the average truck equivalency factor from 75.17 to 54.17 due to increasing structural number from 1 to 6.

Regarding the effect of terminal level of serviceability, Razouki and Radeef (2005) pointed out that for single-unit trucks of type 1.2 and H/B=1.0, SN=2, uphill slope of 13%, the average truck equivalency factor was 72.17 for p_t=2 and 62.64 for p_t =3.

For each type of pavement and truck on uphill slopes, Razouki and Mohee (1999), Razouki and Radeef (2005) and Razouki and Al-Muhanna (2010) reported that for the same total weight of the truck, the damage or the truck equivalency factor caused by a truck with a single rear axle is much higher than that caused by a truck with a rear tandem axle.

For rigid pavements, full-trailer type 1.2+2.2 (total weight of 600kN), H/B=1.0, D= 10 inches (25.4 cm) and p_t =2.5, Razouki and Al-Muhanna (2010) reported that the percent increase in truck equivalency factor was 150% when the uphill slope increased from 0% to18%, while for full-trailer type 1. 22+2.22 with the same weight the percentage was 63%.

For single unit trucks on uphill flexible pavements, Razouki and Radeef (2005) showed that the effect of an increase in truck equivalency factor was quite significant for truck weights exceeding 200kN. For full- trailer trucks on uphill rigid pavements, Razouki and Al-Muhanna (2010) reported that this effect was quite significant for full-trailers having total weights exceeding 400kN.

For flexible pavements, Razouki and Radeef (2005) reported that the effect of increasing the uphill slope is reflected through increasing pavement thickness (e.g. increasing base thickness). They found that for single-unit trucks type 1.2 (total weight about 300 kN), SN=4, H/B=1.0, p_t =2 and uphill slope of 7%, the ratio of truck equivalency factor on uphill slope to that on level highway is about 1.57 causing an increase in base thickness of 52.6mm for uphill pavement.

2.10 Methods of Measuring Axle Loads

There are three main ways of measuring axle loads using either a fixed weighbridge (permanent weighbridge), portable weigh pads or weigh-in-motion equipment.

1) Permanent weighbridges

There are various designs of permanent weighing systems, but most of them comprise a single large weighing platform. With such designs, the vehicles must be driven onto the platform and must be stopped and weighed as each axle in turn mounts of the platform. In this way, the weight of each axle can be calculated by difference (TRL Limited, 2004).

2) Portable weigh pads

Portable weigh pads are small loadometers that can be used singly or in pairs to measure the individual wheel or axle load of a vehicle. The disadvantages of this method are weighing at the roadside is not as safe as at an off-site location and the weighing rate will be slower than can be achieved at a fixed weighbridge. Hence the sample size of the vehicles that are weighed will be smaller (TRL Limited, 2004).

3) Weigh in motion systems

Weigh in motion systems use a weight sensor set into road surface so that all vehicle axle loads are recorded at low traffic speed. This system is capable of giving the complete information, but it is less accurate because of the dynamic effects caused by the motion of the vehicle. This type of weighing is the most expensive option (TRL Limited, 2004).

Note that the permanent weighing stations selected in the study of Al-Muhanna (2008) for weighing the axles of full-trailer types (1.2+2.2, 1.2+2.22, 1.22+2.2 and 1.22+2.22) were Al-Dora grains silo, Karbala silo, Hilla silo and the General Company for Trade of Construction Materials (Karbala).

For completeness, an idea about the various weighing systems involved in previous work is given below.

- In Al-Dora grains silo, the weighing system consists of a concrete permanent weighing platform (3.00 m × 20.00 m) connected to a digital readout unit operating electrically and having a maximum load capacity of 80 tonnes (784.8 kN).
- In Hilla grains silo, the weighing unit consists of a permanent weighing platform of ample size (3.00 m × 18.00 m) connected to a digital readout

unit operating electrically and having a maximum load capacity of 80 tonnes (784.8 kN).

- In the General Company for Trade of Construction Materials and the General Company for Trade of Food Materials (Karbala), the weighing system is the same as in Al-Dora silo.
- In two local stations in Karbala city for weighing dates, the weighing unit consists of a permanent weighing platform of ample size (3.00 m × 18.00-m) connected to a digital readout unit operating electrically and having a maximum load capacity of 80 tonnes (784.8 kN).

2.11 Pull Force between the Tractor and the Trailer Uint

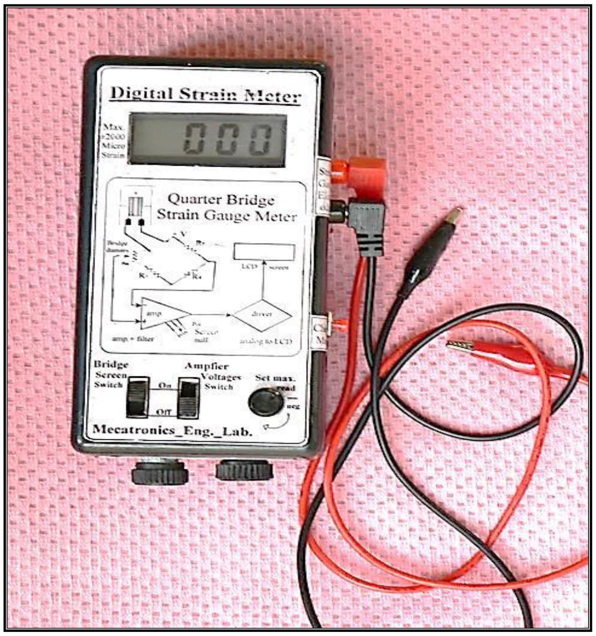
To arrive at a formula that relates the pull force in the drawbar between tractor and trailer units, Al-Muhanna (2008) carried out a survey on (66) full-trailers of type 1.2+2.2, 1.2+2.22, 1.22+2.2 and 1.22+2.22 with different degrees of loading. The instruments used in Al-Muhanna (2008) survey consisted of a digital portable strain meter, strain gauges, and a connecting element between the tractor and the trailer as shown in Plate (2.1).

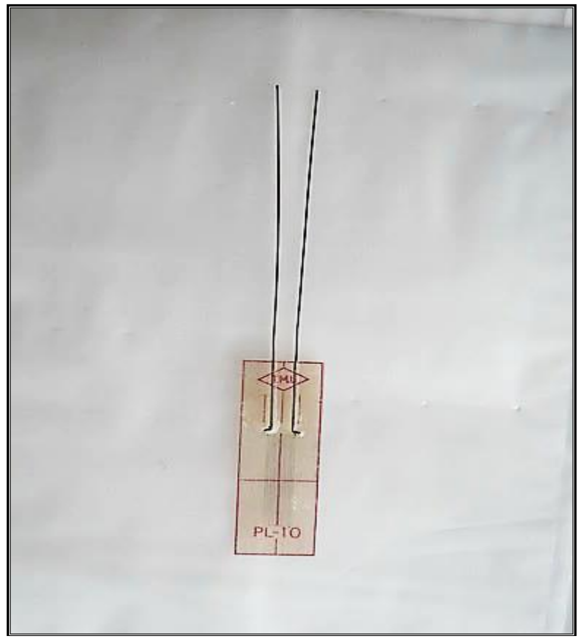
A simple straight connecting element (rod) was manufactured by Al-Muhanna as shown in Plate (2.3) instead of the drawbar between the tractor and the trailer that has nonuniform -shape for the following reasons:

- The connecting rod is straight and has a uniform shape (uniform cross-section). This feature can simplify the analysis.
- To facilitate the survey process by preparing all the required steps at home (fixing the strain gauge to the connecting rod, connecting two wires by

welding to the strain gauge, and isolating the strain gauge's wires from the connecting rod) and not at silos or weighing stations.

- The removable connecting rod allows the same strain gauge to be used in connection with many vehicles. This means that the strain gauge can be used more than one time. This is an economical feature.





(a) **(b)**

Plate (2.1) (a) The digital portable strainmeter (b) The strain gauge(after Al-Muhanna, 2008).

It is worth mentioning that the pull force survey between the tractor and trailer was carried out in the weighing stations after finishing the axle loads survey.Plate (2.4) shows the connection element, strain gauge and the digital strain meter in its position between the tractor and the trailer of one of the trucks surveyed by Al-Muhanna (2008).

A regression analysis was done by Al-Muhanna (2008) for the 66 pull forces data. This regression analysis was done to get a generalized equation for all full trailer types correlating the pull force to the weight of the trailer unit (see equation (2.10)).

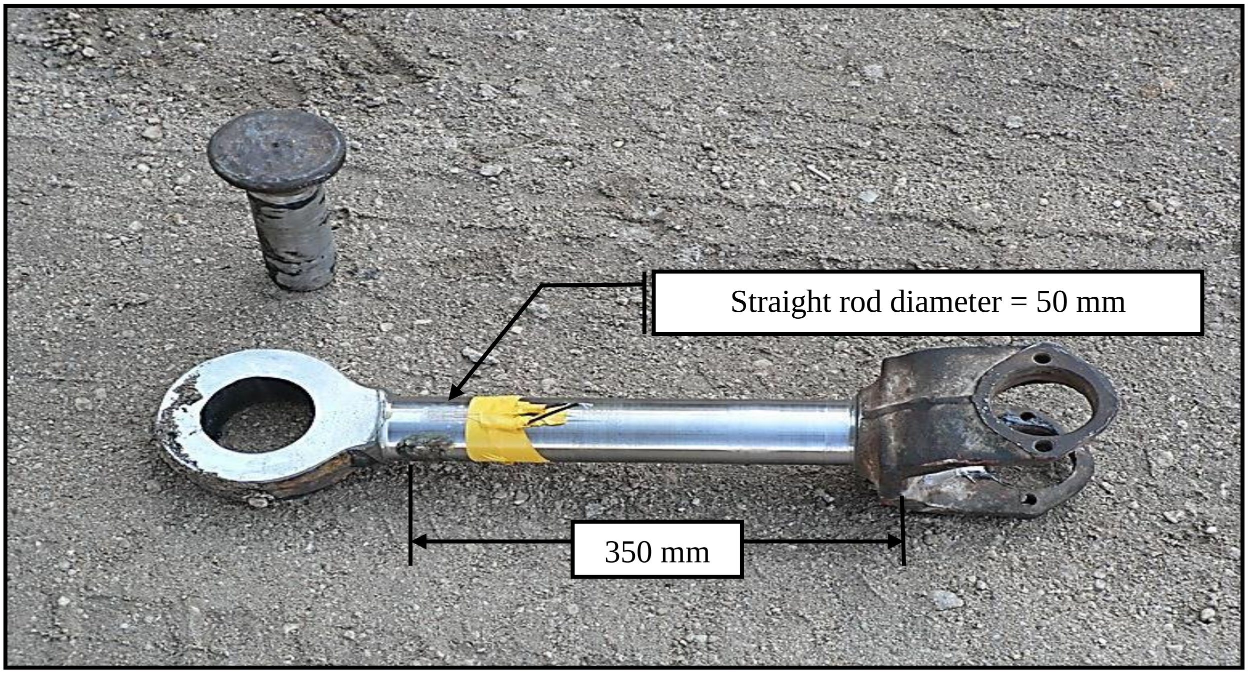


Plate (2.3) The manufactured connecting rod(after Al-Muhanna, 2008).

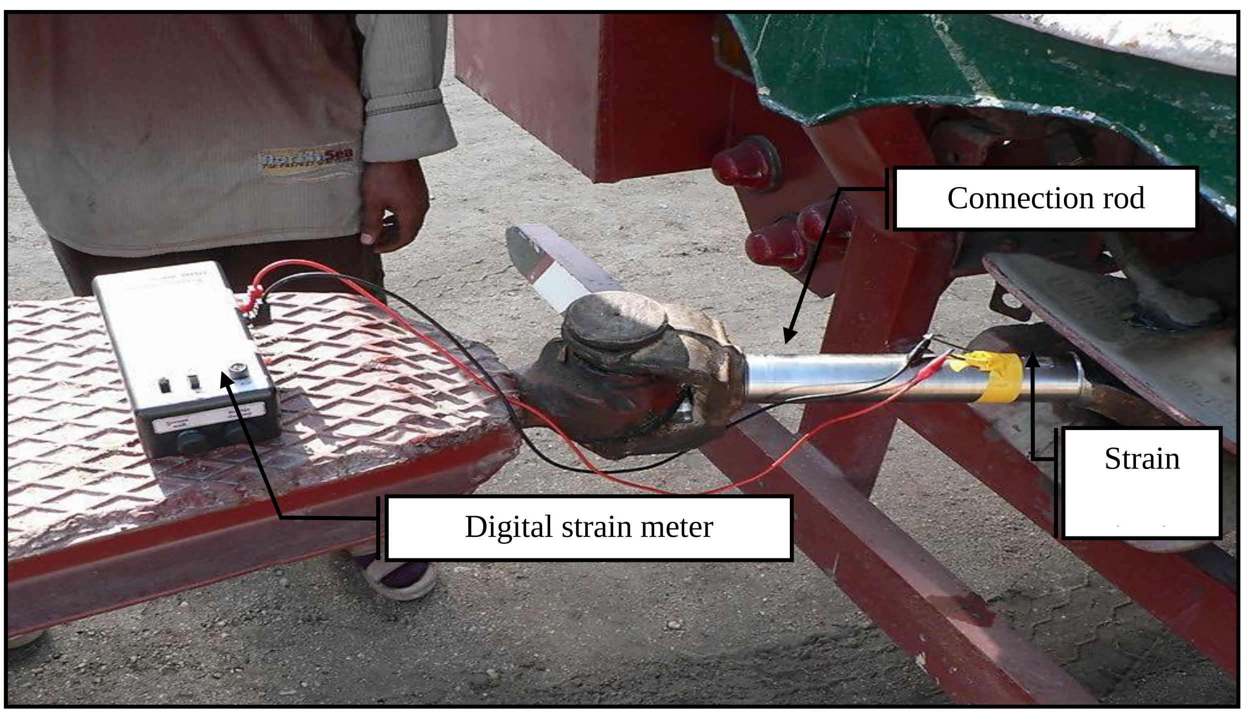


Plate (2.4) Connection rod, strain gauge and the digital strain meter used in Al-Muhanna (2008) survey.

Figure (2.4) shows the scatter diagram together with the following regression line obtained by Al-Muhanna (2008).

$$\mathbf{To = 0.017*(W_2)} \qquad \mathbf{(74\ kN < W_2 < 463\ kN)} \qquad \mathbf{(2.10)}$$

where:

W_2 = total weight of the trailer unit in kN.

To = pull force for the case of level highway in kN.

It is obvious from Figure (2.4) that the linear regression has a higher coefficient of correlation as compared to the non-linear one. This encouraged Al-Muhanna (2008) to adopt the regression line throughout his work. However, it is worth mentioning that this linear regression was based on the restriction of zero y-intercepts at the point of origin.

Al-Muhanna (2008) reported that the percent of pull force to the weight of the trailer ranges from 0.78%to2.1% and that the ratio of the pull force to the weight of the trailer increases with increasing the weight of the trailer.

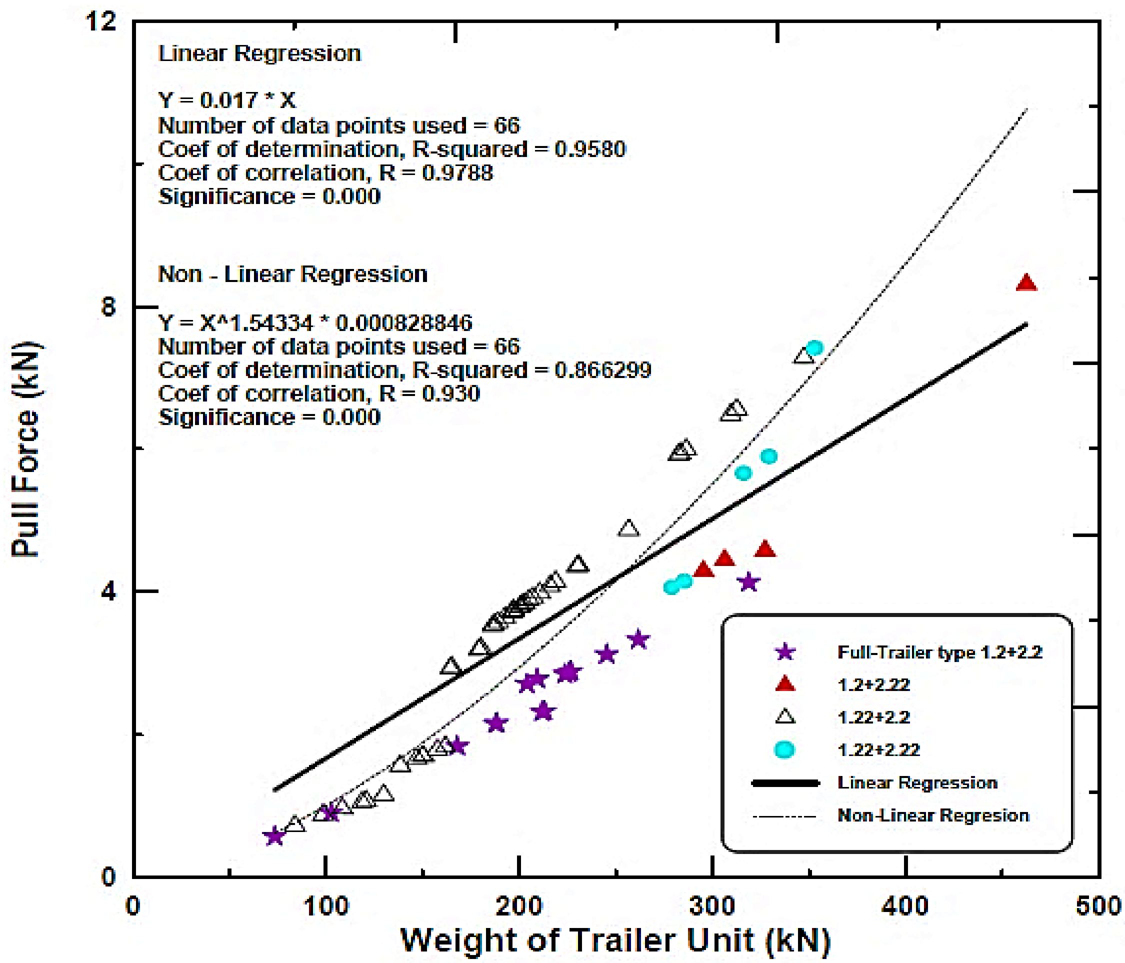


Fig. (2.4) Correlation between pull force and weight of trailer unit (after Al-Muhanna, 2008).

3

CHAPTER THREE

COLLECTION AND ANALYSIS OF BASIC DATA

CHAPTER THREE

COLLECTION AND ANALYSIS OF BASIC DATA

3.1 General

As explained before in Chapter Two, many factors can affect the increase of the damaging effect of full-trailer trucks on uphill flexible pavements. These factors include, among others, the axle load magnitude, magnitude of uphill slope, geometrical characters of full-trailer (especially the length of wheelbase, the height of center of the gravity of the loaded full-trailer above the pavement, and type of each axle) and pavement characteristics. For such purposes, a comprehensive survey should be carried out to provide reliable data for practical use. Such surveys were carried out by Al-Muhanna in some governorates in Iraq during 2008.

For the data to be more reliable, updating is required through a survey in Karbala city followed by a thorough analysis of the whole data collected in this study together with that obtained from Al-Muhanna (2008). This insures a larger and more representative sample size.

3.2 Methodology of study

Figure (3.1) shows the Methodology that was carried out to meet the study objectives.

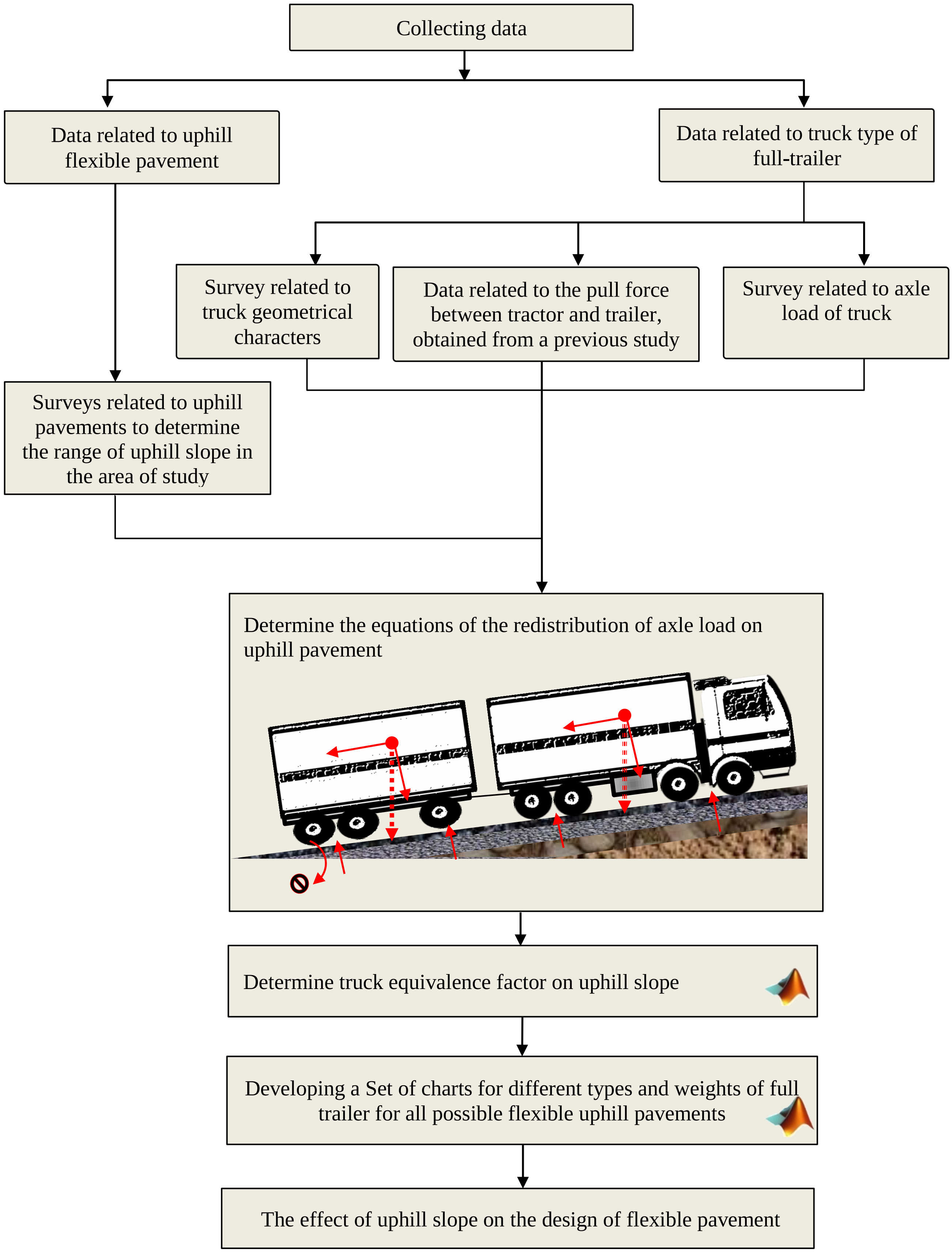


Fig. (3.1) Methodology of study.

3.3 Data collection

Two types of data collection in Karbala city are required. The first type is related to the full-trailer truck characteristics that require an axle load survey, while the second type is related to the maximum existing uphill slope magnitude in Karbala city.

3.3.1 Axle Load Survey

The preliminary survey in this work revealed two new types of full-trailer trucks namely, type 11.2+2.2 and 11.22+2.22.

For this purpose, the survey should be carried out in different stations with enough periods to cover all information needed and to provide sufficient sample size.

3.3.1.1 Survey Stations and Periods

In order to cover as much as possible types of a full-trailer truck carrying various commodities, it was considered necessary to use all useful weighing stations available in Karbala and other near governorates.

For this purpose, two weighing stations are selected in this study. The first station was Karbala Silo and the second was Hilla Silo. The survey periods extended over three months from March 2016 to May 2016.

3.3.1.2 Survey Equipments

As mentioned in Chapter Two (section 2.10), there are various ways of measuring axle loads, It is worth mentioning that only permanent weighbridges were available in the weighing stations in this work. The permanent weighing system consists of two main parts, the platform (where the truck stops on it), which is connected by cables to a readout unit as shown in Plate (3.1) corresponding to Karbala grain silos.

In this study, Karbala silo and Hilla silo were selected for the purpose of axle load survey for full-trailer type (11.2+2.2 and11.22+2.22). For completeness, an idea about the weighing systems involved in this work is given below.

- Hilla grains silo, as mentioned before, consists of a permanent weighing platform of ample size (3.00 m × 18.00 m) and having a maximum load capacity of 80 tonnes (784.8 kN).
- Karbala silo, the weighing system consists of two permanent weighbridges, one is the same as in Al-Dora silo but with 100 tonnes (981-kN) load capacity, while the other consists of a steel platform (3.00 m × 20.00 m) connected to a digital readout unit (as shown in Plate (3.1)) and having a maximum load capacity of 100 tonnes (981 kN).

(a)

(b)

(c)

Plate (3.1) (a) The permanent weighing system in Karbala silo (b) Digital readout unit (c) Cables between platform sensor and digital readout unit.

3.3.1.3 Full-Trailer Truck Weighing Procedure

The weighing of each full-trailer truck was done after registering all the information about the truck type and axle configuration in the axle load survey form shown in Appendix A.

The weighing procedure was done to get each axle load individually. For example, the procedure for weighing the full-trailers of type 11.22+2.22 was as follows:

1. Weighing the front axle (F_{o1}) of the tractor alone (by asking the driver to move slowly on the platform and to stop when only the front axle (steering axle) was on the platform, as shown in Plate (3.2.a)).
2. Weighing all axles of the tractor together (by asking the driver to move slowly forward and to stop when all axles of the tractor are on the platform, as shown in Plate (3.2.b), so that the total weight of the tractor (W_1) can be obtained).
3. Weighing the tractor's axles together with the front axle of the trailer ($W_1^{'}$) (by guiding the driver to move slowly and stop when the tractor unit and front axle of trailer unit were on the platform, as shown in Plate (3.2.c)).
4. Weighing the whole vehicle (tractor and trailer) (W_t) by asking the driver to move the whole full-trailer truck on the platform, as shown in Plate (3.2.d).
5. Asking the driver to move the front axle of the tractor outside the platform for weighing the rear axle of the tractor together with trailer unit, as shown in Plate (3.2.e).

6. Guiding the driver to move forward and stop when the rear axle of the tractor becomes outside the platform for weighing the trailer unit (W_2) alone, as shown in Plate (3.2.f).
7. Weighing the rear axle of the trailer (R_{o2}) alone (by guiding the driver to move forward slowly, and stop when only the rear axle of the trailer becomes on the platform for weighing, as shown in Plate (3.2.g)).

Plate (3.2 a, b, c, d, e, f, and g) shows the weighing procedure for the case of (11.22+2.22) full-trailer in weighing station of Karbala silo.

These weights were read after the digital read out gave a stable reading. It is worth noting that for the permanent weighing system, checking of axle load results was made by comparing the measured total weight of full- trailer truck with that obtained by calculation from the corresponding axle loads. It was found that the average difference in total weight was about ± 100 kg.

Accordingly, the individual axle loads (which were not measured individually) were calculated as follows:

$$\mathbf{R_{o1} = W_1 - F_{o1}} \qquad \textbf{(3.1)}$$

$$\mathbf{F_{o2} = W_1' - W_1} \qquad \textbf{(3.2)}$$

where:

Fo_1, Ro_1 = front and rear axle load of tractor unit, respectively, in tonne.

Fo_2, Ro_2 = front and rear axle load of trailer unit, respectively, in tonne.

W_1, W_2 = total weight of tractor and trailer unit, respectively, in tonne.

W_t = total weight of full-trailer truck, in tonnne.

Similarly, the weighing of full-trailers type (11.2+2.2) followed the same procedure adopted for (11.22+2.22) full-trailer.

(a) Weighing the front tandem axle single tired of the tractor alone.

(b) Weighing all axles of the tractor together (W_1).

(c) Weighing the tractor's axles together with the front axle of the trailer.

(d) Weighing the whole vehicle (tractor and trailer) (W_t).

(e) The front axle of the tractor outside the platform.

(f) Weighing the trailer unit alone (W_2).

(g) Weighing the rear axle of the trailer alone.

Plate (3.2) Vehicle weighing procedure for (11.22+2.22) truck.

3.3.1.4 Axle Load Survey Results

The detailed results of axle load survey of this study together with the results of a survey carried out by Al-Muhanna in (2008) at various stations (as mentioned previously) are given in details in Appendix A.

Table (3.1) shows the type and numbers of vehicles surveyed in this study added to Al-Muhanna (2008) survey at each station of weighing. It is quite obvious from this Table that 46 full-trailer of type 11.2+2.2 and 43 of type 11.22+2.22 were surveyed in this study.

Table (3.2) shows typical axle load results obtained from the survey of this study for full-trailer trucks type (11.2+2.2 and 11.22+2.22) added to Al-Muhanna (2008) survey results for other types of full- trailer trucks.

Table (3.3) shows the maximum and minimum values of each axle load of full-trailer truck surveyed. It is apparent from this table that the front tandem axle load of the tractor unit of the trucks type 11.2+2.2 and 11.22+2.22 are greater than the corresponding rear axle loads for the case of empty trucks, which is completely different from the remaining truck types.

It is obvious from Table (3.3) that the total number of full-trailer trucks covered in the survey of this study added to the survey of Al-Muhanna (2008) study was (343), including (66) full-trailer truck type (1.2+2.2), (29) type (1.2+2.22), (116) type (1.22+2.2), (43) type (1.22+2.22), (46) type (11.2+2.2), and (43) type (11.22+2.22).

Table (3.1) Type and number of full-trailer trucks surveyed at all weighing stations.

Location of weighing stations	Types of trucks surveyed	Number of trucks surveyed		Total number of trucks	
		Loaded	Empty		
Al-Dora Silo	1.2+2.2	3	0	3	18
	1.22+2.2	3	3	6	
	1.2+2.22	2	1	3	
	1.22+2.22	3	3	6	
Karbala Silo	1.2+2.2	12	7	19	166
	1.22+2.2	34	26	60	
	1.2+2.22	7	3	10	
	1.22+2.22	10	6	16	
	11.2+2.2*	22*	9*	31*	
	11.22+2.22*	23*	7*	30*	
Hilla Silo	1.2+2.2	14	6	20	82
	1.22+2.2	14	7	21	
	1.2+2.22	4	2	6	
	1.22+2.22	4	3	7	
	11.2+2.2*	9*	6*	15*	
	11.22+2.22*	10*	3*	13*	
The General Company for Trade of Construction Materials (Karbala)	1.2+2.2	2	4	6	15
	1.22+2.2	3	2	5	
	1.2+2.22	0	0	0	
	1.22+2.22	1	3	4	
The General Company for Trade of Food Materials (Karbala)	1.2+2.2	3	2	5	18
	1.22+2.2	4	3	7	
	1.2+2.22	2	0	2	
	1.22+2.22	3	1	4	
Al-Noor Station for weighing of dates (Karbala)	1.2+2.2	2	2	4	13
	1.22+2.2	3	2	5	
	1.2+2.22	0	1	1	
	1.22+2.22	2	1	3	
Al-Hindiya Station for weighing of dates (Karbala)	1.2+2.2	5	4	9	31
	1.22+2.2	6	6	12	
	1.2+2.22	4	2	6	
	1.22+2.22	3	1	4	
				Total	343

*Full-trailer type 11.2+2.2 and 11.22+2.22 surveyed in this study.

Table (3.2) Typical full-trailer truck axle load results obtained from this study added to Al-Muhanna (2008) survey results.

Axle configuration	L= loaded E= empty	Tractor unit		Trailer unit		W_1 (tonne)	W_2 (tonne)	W_t (tonne)
		F_{o1} (tonne)	R_{o1} (tonne)	F_{o2} (tonne)	R_{o2} (tonne)			
1.2+2.2	E	3.96	6.52	3.22	4.26	10.48	7.48	17.96
1.2+2.2	L	9.98	21.78	13.70	15.02	31.76	28.72	60.48
11.2+2.2*	E	9.88	5.68	5.41	6.44	15.56	11.85	27.41
11.2+2.2*	L	18.46	25.70	14.07	23.71	44.16	37.77	81.93
1.2+2.22	E	3.98	6.28	4.78	7.32	10.26	12.10	22.36
1.2+2.22	L	10.14	22.30	14.66	23.34	32.44	38.00	70.44
1.22+2.2	E	5.14	10.32	4.14	5.18	15.46	9.32	24.78
1.22+2.2	L	8.42	20.70	9.58	11.52	29.12	21.10	50.22
1.22+2.22	E	5.08	9.20	5.20	9.12	14.28	14.32	28.60
1.22+2.22	L	8.78	20.84	12.12	21.78	29.62	33.90	63.52
11.22+2.22*	E	9.48	8.34	5.23	7.89	17.82	13.12	30.94
11.22+2.22*	L	19.09	33.43	12.41	23.97	47.43	36.38	83.80

L= loaded truck (fully or partially loaded).
E= empty truck.
F_{o1}= front axle load of tractor unit, in tonne.
R_{o1} = rear axle load of tractor unit, in tonne.
W_t = total weight of full-trailer truck, in tonnne = W_1+ W_2.
*The type of full-trailer truck surveyed in this study.
F_{o2} = front axle load of trailer unit, in tonne.
R_{o2} = rear axle load of trailer unit, in tonne.
W_1 = total weight of tractor unit, in tonne =Fo_1+Ro_1.
W_2 = total weight of trailer unit, in tonne =Fo_2+Ro_2.

Table (3.4) shows a summary of the numbers of each type of axle surveyed at all stations together with the corresponding maximum and minimum axle loads.

Table (3.4) also reveals that the total number of axles covered in this study was (254) for front single axles, (89) front tandem axles, (712) rear single axles and (317) rear tandem axles.

Table (3.3) Maximum, minimum and average axle load for each full-trailer truck and number of each full-trailer truck surveyed.

Case		Maximum axle load		Minimum axle load		Average axle load		No. of truck observations
		(tonne)	(kN)	(tonne)	(kN)	(tonne)	(kN)	
1.2+2.2	F_{o1}	11.320	111.049	3.960	38.847	7.640	74.92	66
	R_{o1}	27.220	267.028	6.520	63.961	16.510	161.91	
	F_{o2}	17.260	169.321	3.220	31.588	10.521	103.18	
	R_{o2}	19.400	190.314	4.260	41.790	11.257	110.39	
1.2+2.22	F_{o1}	12.320	120.859	3.980	39.043	8.085	79.29	29
	R_{o1}	28.320	277.819	6.280	61.606	17.548	172.09	
	F_{o2}	18.500	181.485	4.780	46.891	11.046	108.32	
	R_{o2}	28.640	280.958	7.320	71.809	18.238	178.85	
1.22+2.2	F_{o1}	11.660	114.385	4.640	45.518	8.365	82.03	116
	R_{o1}	34.580	339.229	7.320	71.809	19.876	194.92	
	F_{o2}	18.640	182.858	3.480	34.138	9.611	94.25	
	R_{o2}	20.560	201.693	4.500	44.145	11.672	114.46	
1.22+2.22	F_{o1}	11.640	114.188	5.080	49.834	7.853	77.01	43
	R_{o1}	30.580	299.989	9.200	90.252	19.299	189.26	
	F_{o2}	17.600	172.656	5.200	51.012	10.629	104.23	
	R_{o2}	29.200	286.452	9.120	89.467	19.507	191.3	
11.2+2.2*	F_{o1}	21.990	215.620	9.880	97.070	17.459	171.21	46
	R_{o1}	26.430	259.170	5.680	55.700	20.530	201.33	
	F_{o2}	14.070	137.960	5.410	53.040	10.718	105.11	
	R_{o2}	24.630	241.510	6.440	63.150	17.180	168.48	
11.22+2.22*	F_{o1}	20.000	196.130	9.480	92.970	16.402	160.85	43
	R_{o1}	33.430	327.840	9.840	96.500	23.533	230.78	
	F_{o2}	14.160	138.870	5.230	51.290	9.695	95.08	
	R_{o2}	25.520	250.270	7.890	77.370	16.115	158.03	
							Total	343

* The type of full-trailer truck surveyed in this study.
Note: 1 tonne = 9.81 kN.

Table (3.4) Summary of axle load survey results.

Axle type	Maximum axle load		Minimum axle load		Average axle load		legal limit of axle load		Number of surveyed axles
	(tonne)	(kN)	(tonne)	(kN)	(tonne)	(kN)	(tonne)	(kN)	
S.A.S	12.320	120.859	3.960	38.847	8.224	80.677	7	68.65	254
T.A.S *	21.990	215.62	9.42	92.38	16.25	159.43	10-11**	98.1-107.8**	89
S.A	28.320	277.819	3.220	31.588	17.827	174.882	13	127.49	712
T.A	34.580	339.229	7.320	71.809	19.857	194.797	20	196.13	317

S.A.S. = Single axle single tired, T.A.S. = tandem axle single tired, S.A. = Single axle dual tires, T.A. = tandem axle.
*New type of axle surveyed in this study. ** Axle load limit according to Registration National Heavy Vehicle Reform, New South Wales (2001)
Note: 1 tonne = 9.81 kN.

The maximum axle loads obtained from the survey were 12.320, 21.990, 28.320, and 34.580 tonnes (120.859, 215.510, 277.819 and 339.229 kN) for front single, front tandem, rear single, and rear tandem axle load respectively. Compared with the legal limits of axle loads in Iraq according to State Commission for Roads and Bridges in Iraq (SCRB, 2009), namely 7, 13 and, 20 tonnes (68.65, 127.49 and 196.13 kN) for front single, rear single, and rear tandem axle load respectively. the observed maximum front axle load or The overloaded front single, front tandem, rear single, and rear tandem axle load resulting into 12.32/7= 1.76=176%, 21.99/11= 1.99 = 199%, 28.320/13= 2.18= 218%, 34.580/ 20= 1.73= 173% times its legal limit respectively.

3.3.1.5 Sample Size

In order to get reliable results, it is important to determine the proper sample size when carrying out any survey. This fact was emphasized by Cochran (1977), who reported that “too large sample implies a waste of resources, and too small sample diminishes the utility of the results”. Due to the importance of axle loads in this study, the sample size will be determined on the basis of axle load.

Such an approach was adopted in various previous studies (Mirza, 1990; Ali, 1991; Mohee, 1992; Al-Muhanna, 2008).

The required sample size can be determined as follows (O'Flaherty, 1988; Kreyszig, 2006):

$$\mathbf{N \geq \frac{4s^2}{E^2}} \qquad \textbf{(3.3)}$$

where:

N = sample size.

s = standard deviation of the sample.

E = maximum allowable error.

It is clear that the required sample size is affected by the allowable error. Therefore, the maximum allowable error should be defined in advance.

On the basis of the class width of axle load frequency distribution histogram, Kamaludeen (1987) reported that for high accuracy and practical sample size, the maximum error should not exceed half the class width (class interval). In this study, to achieve the required sample size the maximum allowable error used is half the class width of the axle load frequency distribution histogram.

Following O'Flaherty (1988), a class interval of convenient size is obtained using the following formula:

$$\mathbf{C = \frac{R}{1 + 3.322\log_{10}(N)}} \qquad \textbf{(3.4)}$$

where:

C = class interval.

N = number of observations.

R = range between largest and smallest value for a given set of observations.

Tables (3.5) and (3.6) show the class widths adopted in this study for full-trailer trucks type (11.2+2.2) and (11.22+2.22).

Table (3.5) Selection of class widths for full-trailer truck type (11.2+2.2).

Reference for computing the class widths	Min. value (tonne)	Max. value (tonne)	No. of observations	Calculated class widths (tonne)	Adopted class widths (tonne)
Front Axle Load of the Tractor unit	9.88	21.99	46	1.86	2.00
Rear Axle Load of the Tractor unit	5.68	26.43	46	3.18	3.50
Front Axle Load of the Trailer unit	5.41	14.07	46	1.33	1.50
Rear Axle Load of the Trailer unit	6.44	24.63	46	2.79	3.00

Table (3.6) Selection of class widths for full-trailer truck type (11.22+2.22).

Reference for computing the class widths	Min. value (tonne)	Max. value (tonne)	No. of observations	Calculated class widths (tonne)	Adopted class widths (tonne)
Front Axle Load of the Tractor unit	9.48	20.71	43	1.75	2.00
Rear Axle Load of the Tractor unit	9.84	33.43	43	3.67	4.00
Front Axle Load of the Trailer unit	5.23	14.16	43	1.39	1.50
Rear Axle Load of the Trailer unit	7.89	25.52	43	2.77	3.00

It is quite obvious from these tables that the adopted class widths are convenient and close enough to those calculated using equation (3.4).

Table (3.7) shows the actual sample size obtained in this study compared with the required sample size for each axle of different types of full-trailers surveyed as obtained from equation (3.3). It is quite obvious that the adopted sample size of the survey of this work is quite satisfactory.

Table (3.7) Required and Actual Sample Size.

Type of full-trailer	Reference for computing the sample size.	E (1)	N_r (2)	N (3)	% (4)
11.2+2.2	Front Axle Load of the Tractor unit	1.000	23	46	51.68
	Rear Axle Load of the Tractor unit	1.750	23		
	Front Axle Load of the Trailer unit	0.750	21		
	Rear Axle Load of the Trailer unit	1.500	27		
11.22+2.22	Front Axle Load of the Tractor unit	1.000	25	43	48.31
	Rear Axle Load of the Tractor unit	2.000	32		
	Front Axle Load of the Trailer unit	0.750	28		
	Rear Axle Load of the Trailer unit	1.500	25		

(1): E= maximum allowable error after half class width criterion (tonne).
(2): Nr= required minimum sample size (see eq. (3.2)).
(3): N = actual sample size.
(4): Percentage of each type of the full-trailers surveyed.

3.3.2 Some Geometrical Characteristics of Full-Trailer Trucks

As mentioned previously in chapter two, the geometrical characteristics of full-trailer trucks such as the length of wheelbase, height of center of gravity of loaded truck above the pavement, the axle geometry and the height of the drawbar (between the tractor unit and the trailer) above the pavement have an important effect on increasing the damaging effect of full trailer trucks on uphill pavement.

The measurement of these geometrical characteristics was done after the completion of the weighing procedure and when the vehicle left the weighing system and stopped far away from it. This survey covered the whole sample of trucks included in the axle load survey.

As shown in Figure (3.2), for tractor type (11.2) the distances (S_{11}) and (S_{12}) were measured and the wheelbase was calculated as:

$$\mathbf{B_1 = S_{11}/2 + S_{12}} \qquad \textbf{(3.5)}$$

However, for tractor type (11.22) the distances (S_{11}), (S_{12}) and (S_{13}) were measured and the wheelbase was calculated as:

$$\mathbf{B_1 = S_{11} / 2 + S_{12} + S_{13}/2} \qquad \textbf{(3.6)}$$

For trailer type (2.2), the wheelbase (B_2) was measured directly as shown in Figure (3.2). However, for trailer type (2.22) the distances (S_{21}) and (S_{22}) were measured, and the wheelbase was calculated as:

$$\mathbf{B_2 = S_{21} + S_{22} / 2} \qquad \textbf{(3.7)}$$

Table (3.8) shows typical geometrical characteristics results obtained from the survey of this study for full-trailer trucks type (11.2+2.2 and 11.22+2.22).

The geometrical characteristics survey form and the detailed survey results of axle geometry and vehicle dimensions for all degrees of loading of full-trailers type (11.2+2.2) and (11.22+2.22) are given in Appendix B.

As shown in Figure (3.2), the elevation of both ends of the drawbar (between the tractor unit and the trailer) above the pavement (E_1) and (E_2) for full-trailer truck type (11.2+2.2) and (11.22+2.22) were measured using steel tape.

It was noticed that a small difference existed in the heights between the two ends of the drawbar fluctuating between 0 and 6 cm. This small difference in elevation of both ends was neglected. It was found that in 84% of cases, the elevation was 100 cm and it was fluctuating from 93 to 99 cm for the other 16%. Al-Muhanna (2008) pointed out that the difference in height between the two ends of the drawbar for full-trailer trucks type (1.2+2.2), (1.2+2.22), (1.22+2.2), and (1.22+2.22) fluctuated between 0 and 4 cm.

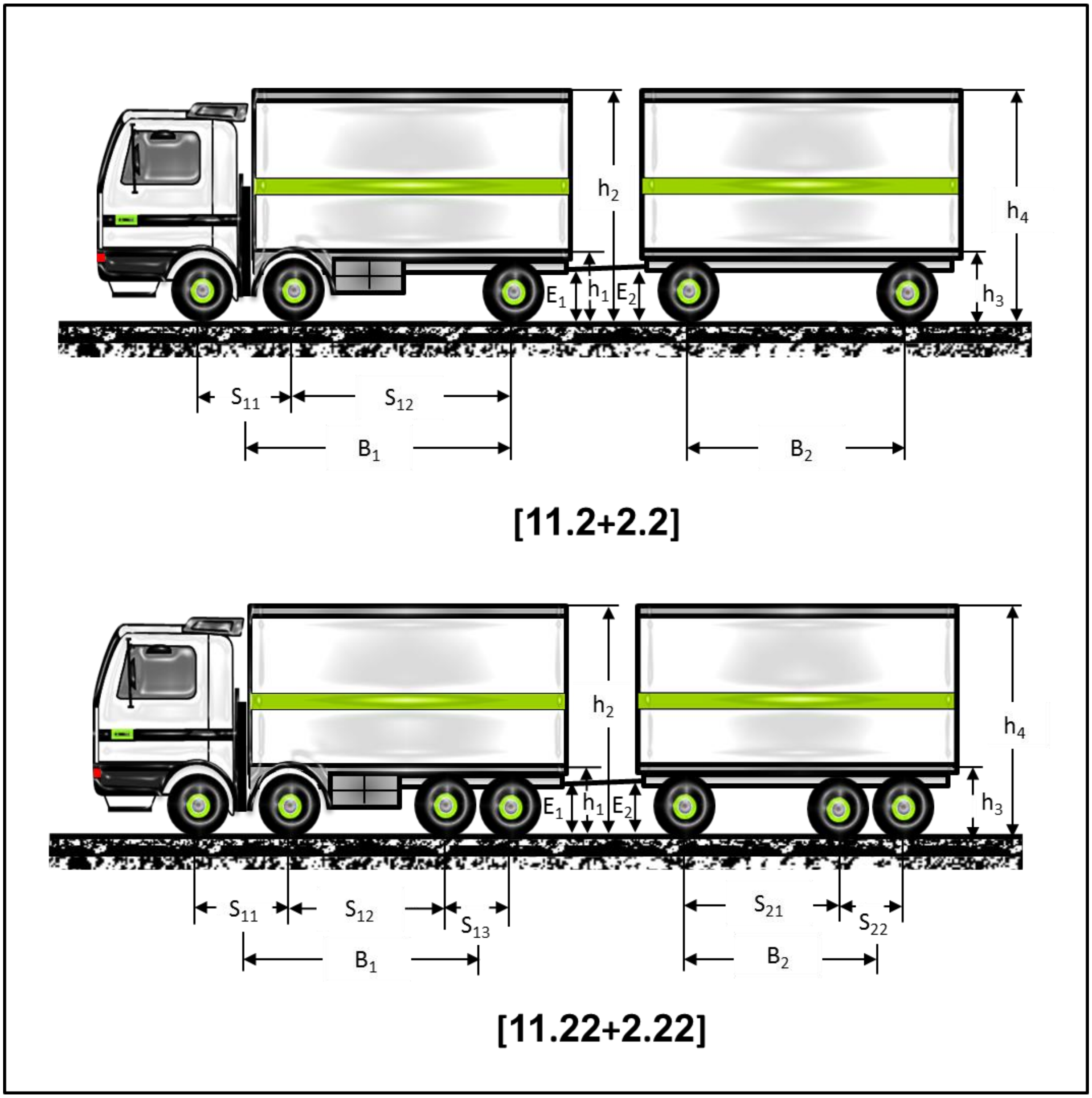


Fig. (3.2) Vehicles dimensions for (11.2+2.2), and (11.22+2.22) full –trailer trucks.

However, he found that in (87%) of cases, the elevation was 100 cm and it was 95 cm for the others (13%). Therefore, it was considered logical to assume that the height of the drawbar between the tractor unit and the trailer for all types of full-trailer trucks is constant and equal to 100 cm.

Table (3.8) Typical results of the geometrical characteristics for full-trailer trucks type (11.2+2.2) and (11.22+2.22).

Type of full-trailer truck	Tractor unit						Trailer unit				
	S_{11} (mm)	S_{12} (mm)	S_{13} (mm)	B_1 (mm)	h_1 (mm)	h_2 (mm)	S_{21} (mm)	S_{22} (mm)	B_2 (mm)	h_3 (mm)	h_4 (mm)
11.2+2.2	1700	3860	……	4710	1276	2870	……	……	5440	1256	3200
11.2+2.2	1830	3960	……	4875	1298	3200	……	……	5590	1539	3300
11.2+2.2	1920	2203	……	3163	1345	2890	……	……	3880	1600	3020
11.22+2.22	1680	2700	1360	4220	1300	3200	4300	1300	4950	1490	3480
11.22+2.22	1770	2218	1270	3738	1460	3700	3320	1340	3990	1400	3690
11.22+2.22	1823	3629	1320	5200	1300	2734	3578	1245	4200	1600	2890

It is worth mentioning that the horizontal distance between the two ends of the drawbar was found 270 cm shown in Figure (3.3) corresponding to 11.22+2.22 full trailer truck.

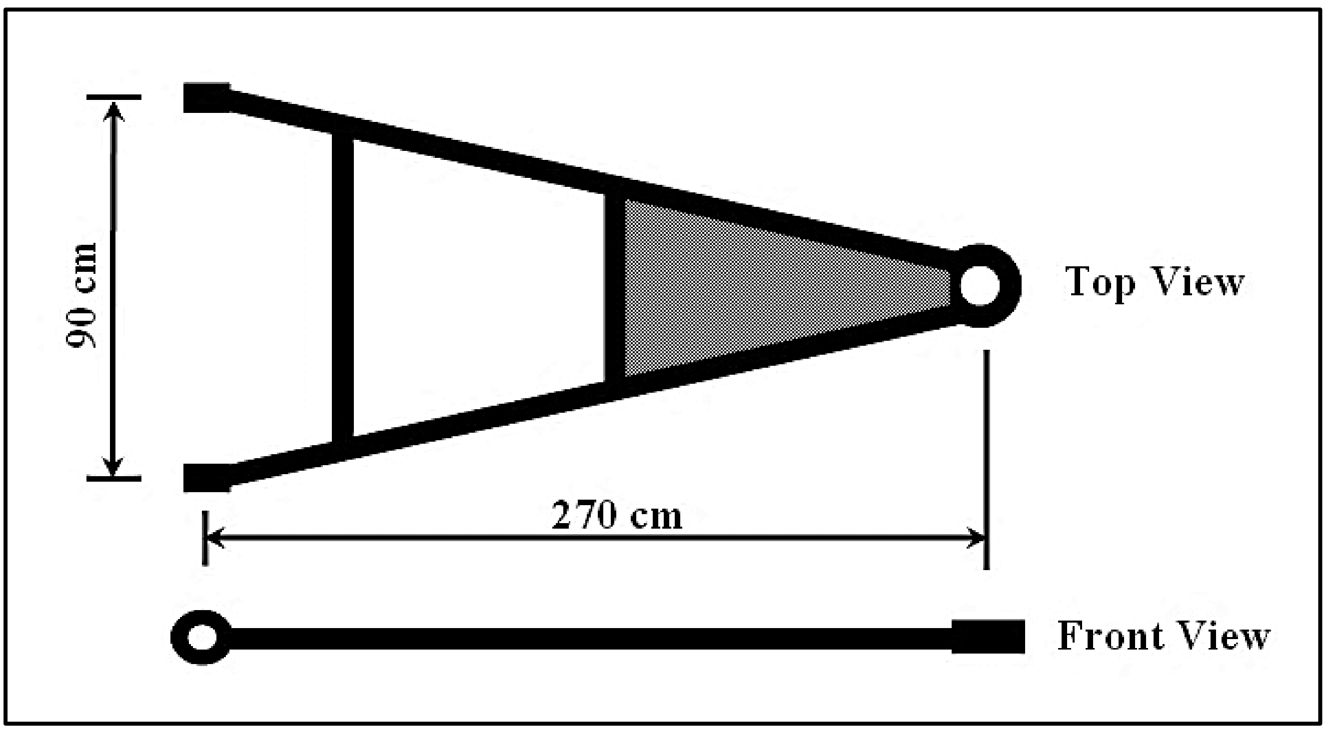


Fig. (3.3) Connecting element (drawbar) between the tractor and trailer units of (11.22+2.22) truck (for Mercedes, 1998).

3.3.3 <u>Upgrades Surveying</u>

3.3.3.1 Upgrade Survey Equipment

The instruments used in the upgrade survey were the measuring tape of (50-m) length, leveling staff and level, as shown in Plate (3.3).

The measuring tape shown in Plate (3.3a) was used to measure the horizontal distance (length of the horizontal interval) on upgrade.

The leveling staff shown in Plate (3.3a) used in this survey was of (4 m) length with major graduations at (100 mm) interval, and the minor graduations were at (10 mm) interval. The level for measuring the elevation of selected stations was a Kern tilting level as shown in Plate (3.3b).

(a) **(b)**

Plate (3.3) (a)Leveling staff and tape (b) Kern tilting level.

3.3.3.2 The Uphill Surveying Process

To determine the maximum uphill slope of existing highways and interchanges in Iraq, a survey is carried out in this work on Karbala roads and interchanges to be added to the survey carried out by Al-Muhanna (2008) in some governorates in Iraq such as Sulaimaniya, Erbil and Dohouk.

The surveying process adopted for measuring the maximum slope of uphill pavements is as follows:

1. The length of the uphill segment is divided into some horizontal distances, the length and number of horizontal distances depended on the length and topography of the highway. A horizontal distance of (5 m) is used for the case of relatively steep slopes and (10 m) for normal slopes (the distance was measured by the tape).
2. The level is set up at a suitable position on the shoulder of the uphill roadway.
3. The level readings were taken (by using the leveling staff) at each station on uphill roadway edge as shown in Plate (3.4).

The maximum uphill slope (tanα) can then be calculated from the following equation:

$$\tan\alpha = \frac{\text{max. difference in elevation}}{\text{horizontal length of interval}} \qquad \textbf{(3.8)}$$

Table (3.9) presents part of the readings obtained from the surveying for determining the maximum uphill slope of Karbala-Ein Al-Tamur road of (1158 m) length.

Plate (3.5) shows a full-trailer truck type (11.22+2.22) moving on an uphill slope on Karbala – Ein Al-Tamur road.

Plate (3.4) Upgrade survey on Karbala – Ein Al Tamur road.

Plate (3.5) Full-trailer type (11.22+2.22) on Karbala – Ein Al Tamur road.

In addition to the upgrade survey on Karbala – Ein Al Tamur road, the survey also covered various interchanges in Karbala city such as Al-Imam Ali interchange; Al-Malab interchange and Fatima Al-Zahraa interchange. All the data obtained from the uphill slopes surveyed on both Karbala – Ein Al Tamur road and Karbala city interchanges are shown in Appendix (C).

Table (3.9) Leveling for determining the maximum uphill slope of Karbala – Ein Al-Tamur road.

Level reading (m)	Horizontal distance (m)	Slope (%)	Maximum upgrade (%)
4.500	0.00		
4.160	5.00	6.80	
3.810	10.00	7.00	
3.459	15.00	7.00	
3.109	20.00	7.00	7.00
2.759	25.00	7.00	
2.417	30.00	6.84	
2.076	35.00	6.82	

Table (3.10) gives the readings obtained from the surveying for determining maximum uphill slope in Al-Imam Ali interchange (in Karbala city) at ramp (loop) No.2 shown in Figure (3.4).

Table (3.10) Leveling for determining the maximum uphill slope at Imam Ali - interchange (loop No.2).

Level reading (elevation)	Horizontal distance (m)	Slope (%)	Max upgrade (%)
3.674	0.00		
3.435	5.00	4.78	
3.185	10.00	5.00	5.00
2.935	15.00	5.00	
2.684	20.00	5.00	
2.440	25.00	4.88	

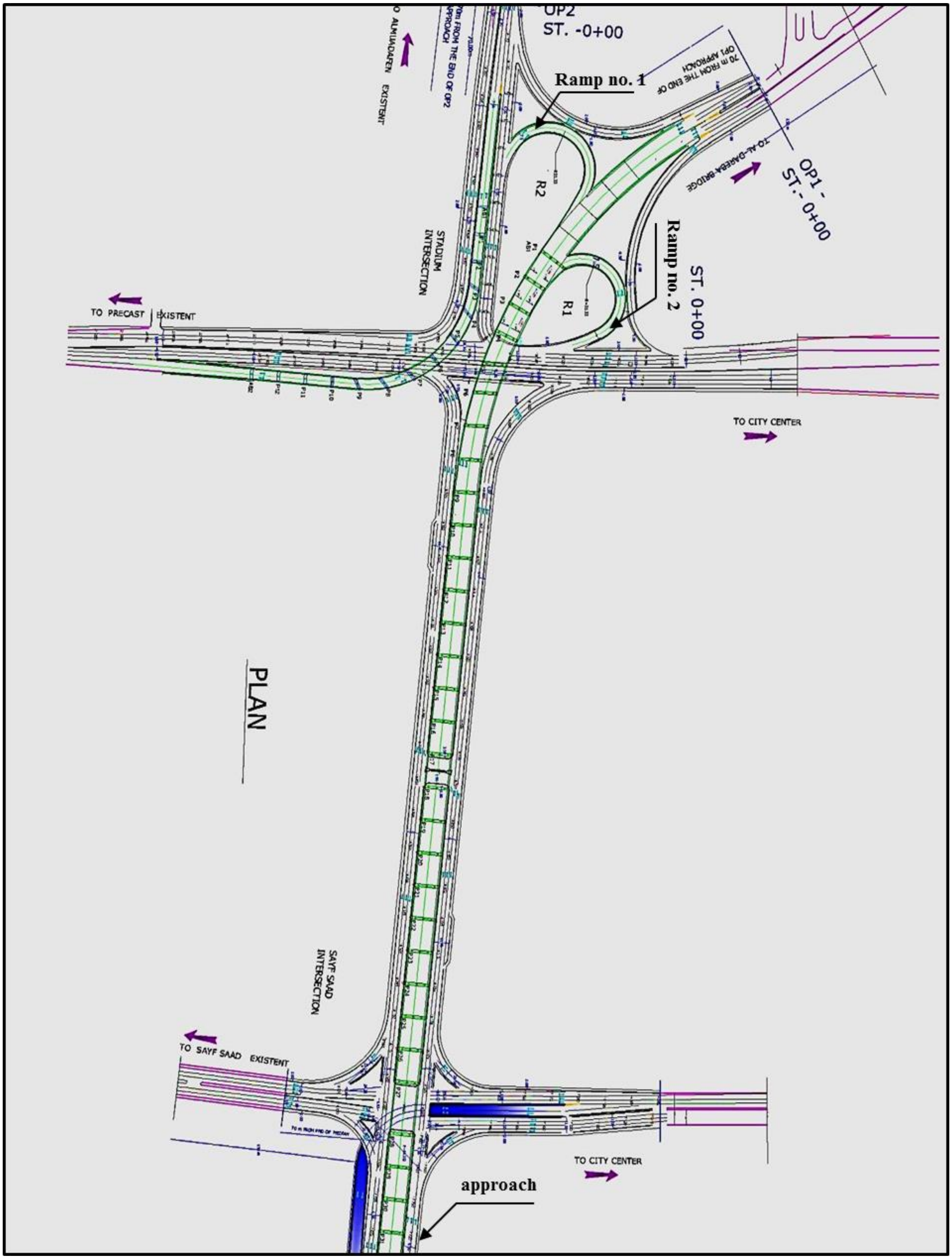


Fig. (3.4) Al-Imam- Ali interchange.

Table (3.11) summarizes the most important results concerning the maximum uphill slope for the different roads and interchanges surveyed in this work together with those studied by Al-Muhanna (2008).

Table (3.11) Upgrade magnitudes, lengths and locations of road and interchanges sections surveyed in this work and those surveyed by Al-Muhanna (2008).

City	Roads	Length of uphill section (m)	Max. uphill slope (%)
Dohouk	Solaf-Al Imadiya	300	12.0
	Sersenk-Ashawa Cave	60	10.0
Sulaimaniya	Khalikan-Sad Dokan	40	14.0
		1400	10.0
		640	16.0
	Chamchamal-Sangaw	225	12.0
Erbil	Shaqlawa-Hareer	250	18.0
	Hareer-Khalifan	300	17.0
Karbala*	Ein Al Tamur	1158	7.0

City	Interchanges		Length of uphill section (m)	Max. uphill slope (%)
Karbala*	Al-Imam Ali interchange	Ramp no.1	198	5.0
		Ramp no.2	127	5.0
		Approach	100	4.0
	Al- Malab interchange		139	5.0
	Fatima Al-Zahraa interchange		240	4.5

*The Sites that were surveyed for the uphill slope in this study.

It is interesting to note at this stage that the Rasan-Kalifan highway in Iraq showed a maximum grade of 8.8% as can be seen from its corresponding sheet No.55 (Directorate General of Roads and Bridges, 1968). For designing multi-story car parks, Kadiyali (1991) recommended the use of 1 in 10 gradies and 1 in 8 (i.e. 12.5%) for very short ramps.

3.4 Adopted Correlation between Pull Force and Weight of Trailer Unit

As discussed under section 2.10, Al-Muhanna (2008) presented two regression equations that correlate the pull force with the weight of trailer unit. However, his linear relationship was restricted to the case of zero y-intercept. To avoid this restriction, it was decided to do the linear regression analysis in this work without any restriction on the y-intercept. For this purpose, the 66 pull force data obtained by Al-Muhanna (2008) are to be correlated in this work with the corresponding weights of the trailer units as shown in Figure (3.5). Using the software Excel (2014) and SPSS, the following equation was obtained for the case of linear regression:

$$\mathbf{To = 0.0214 \times W_2 - 1.1239} \qquad \mathbf{(74\ kN < W_2 < 463\ kN)} \qquad \mathbf{(3.9)}$$

where:

W_2 = total weight of the trailer unit in kN.

To = pull force for the case of level highway in kN.

Note that the corresponding coefficient of determination was $R^2 = 0.827$ and significant value p = 0.000 that is less than 0.05 (see Table (3.12.a)) indicating strong correlation (Anderson and Sclove, 1978). Also, the coefficients of module were significance as show in Table (3.12.b).

Table (3.12) Linear correlation between pull force and weight of trailer unit.

a. Model Summary and Parameter Estimates

Equation	Model Summary								Parameter Estimates	
	R	R Square	Adjusted R Square	Std. Error of the Estimate	F	df1	df2	Sig.	Constant	b1
Linear	.910	.827	.825	.725	306.608	1	64	.000	-1.124-	.021

The independent variable is w.

b. Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
w	.021	.001	.910	17.510	.000
(Constant)	-1.124-	.279		-4.029-	.000

Similarly, the nonlinear correlation analysis yielded the following equation that is exactly that given in Figure (2.4), which was obtained by Al-Muhanna (2008):

$$\mathbf{To = 0.0008 \times (W_2)^{\wedge 1.5433} \qquad (74 < W_2 < 463) \qquad (3.10)}$$

The corresponding coefficient of determination was R^2=0.866 and significant value p = 0.000 that is less than 0.05 (see Table (3.13.a)) indicating strong correlation (Anderson and Sclove, 1978). Also, the coefficients of module are significance as show in Table (3.13.b).

Table (3.13) Non-linear correlation between pull force and weight of trailer unit.

a. Model Summary and Parameter Estimates

Equation	Model Summary								Parameter Estimates	
	R	R Square	Adjusted R Square	Std. Error of the Estimate	F	df1	df2	Sig.	Constant	b1
Power	.931	.866	.864	.218	414.680	1	64	.000	.001	1.543

The independent variable is w.

b. coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(w)	1.543	.076	.931	20.364	.000
(Constant)	.001	.000		2.477	.016

The dependent variable is ln (t).

However, as the coefficient of correlation for the nonlinear equation is higher than that for the linear one, equation (3.10) will be adopted in this work.

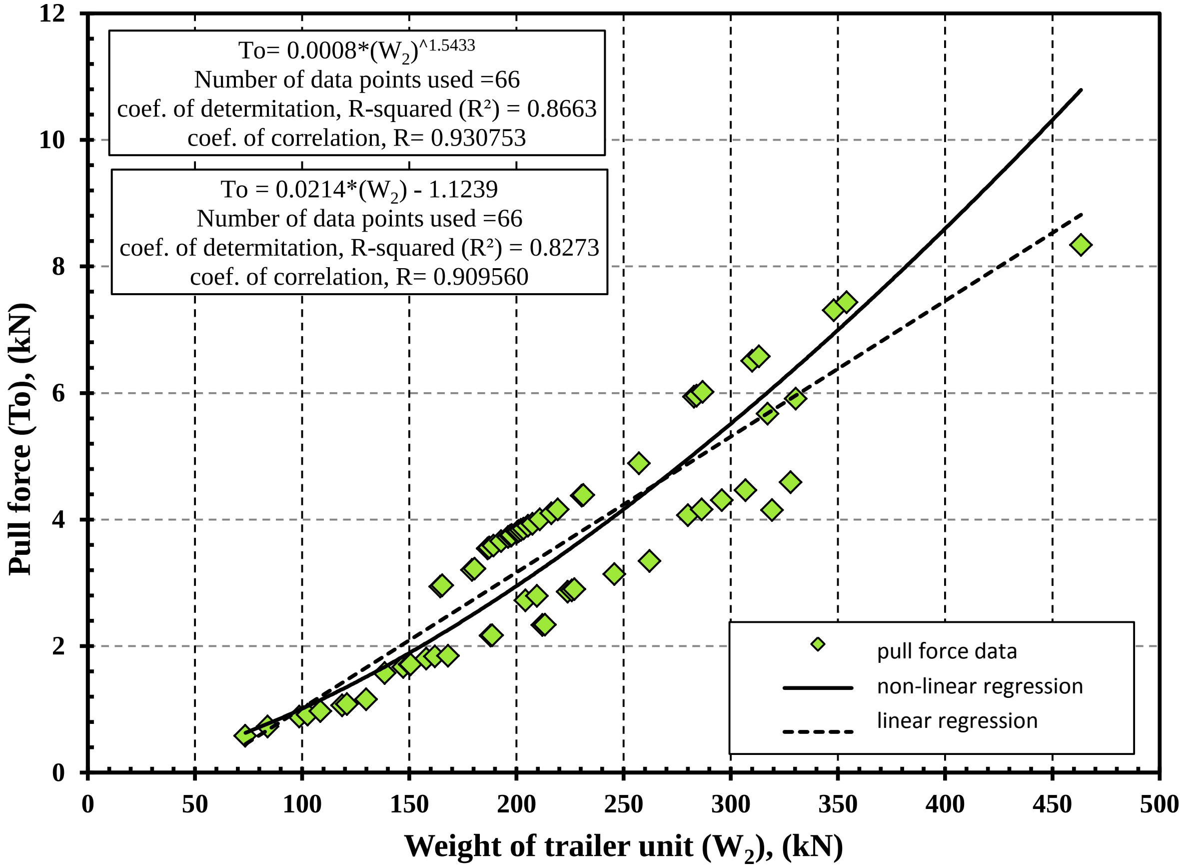


Fig. (3.5) Correlation between pull force and weight of trailer unit.

Finally, it is worth noting that the pull force formula given by equations (3.9 and 3.10) was obtained by force measurements on rigid pavements (Al-Muhanna, 2008). However, the factors that affect this force are the same for both cases except the rolling resistance which may be different for different pavement types. However, equation (2.5) for the rolling resistance did not differentiate between rigid and flexible pavements but focused on the weight and vehicular speed. This supports the use of equation (3.10) for this work.

3.5 Data Analysis

3.5.1 Axle Load Survey Data Analysis

The data collected from the axle load survey that was carried out for full-trailer trucks of type (11.2+2.2) and (11.22+2.22) should be analyzed. In order to study the characteristics of axle loads, the collected data is to be represented by histograms, and the corresponding distributions have been determined. This requires the selection of suitable class intervals and testing the normality of the frequency distribution of the collected data using the chi-square goodness of fit test. The class interval for each axle of tractor and trailer unit of the full-trailer truck type, was calculated previously under section 3.2.1.5 and shown in Tables (3.5) and (3.6). It is quite obvious from these tables that the adopted class widths are convenient and close enough to those calculated using equation (3.4).

For tractor unit type (11.2), Figure (3.6.a) shows the front tandem axle load frequency distribution histogram together with the corresponding normal distribution curve. The chi-square goodness of fit test (see Appendix D) reveals that the hypothesis of normality is accepted for a level of significance (α=5%). It is quite obvious from this Figure that the front tandem axle load range is wide. The maximum front tandem axle load obtained from the survey of this study was 21.99 tonne (125.65 kN) which is much greater than the legal limit of 10 to 11 tonne (98.1 to 107.8 kN) according to Registration National Heavy Vehicle Reform, New South Wales (2001), which is relatively high indicating the need for a legal axle load limit for such axle in Iraq. Figure (3.6.b) shows the frequency distribution histogram of the rear single axles of tractor unit type (11.2). It is obvious from this figure that the distribution follows the normal distribution and that there is a serious overloading problem.

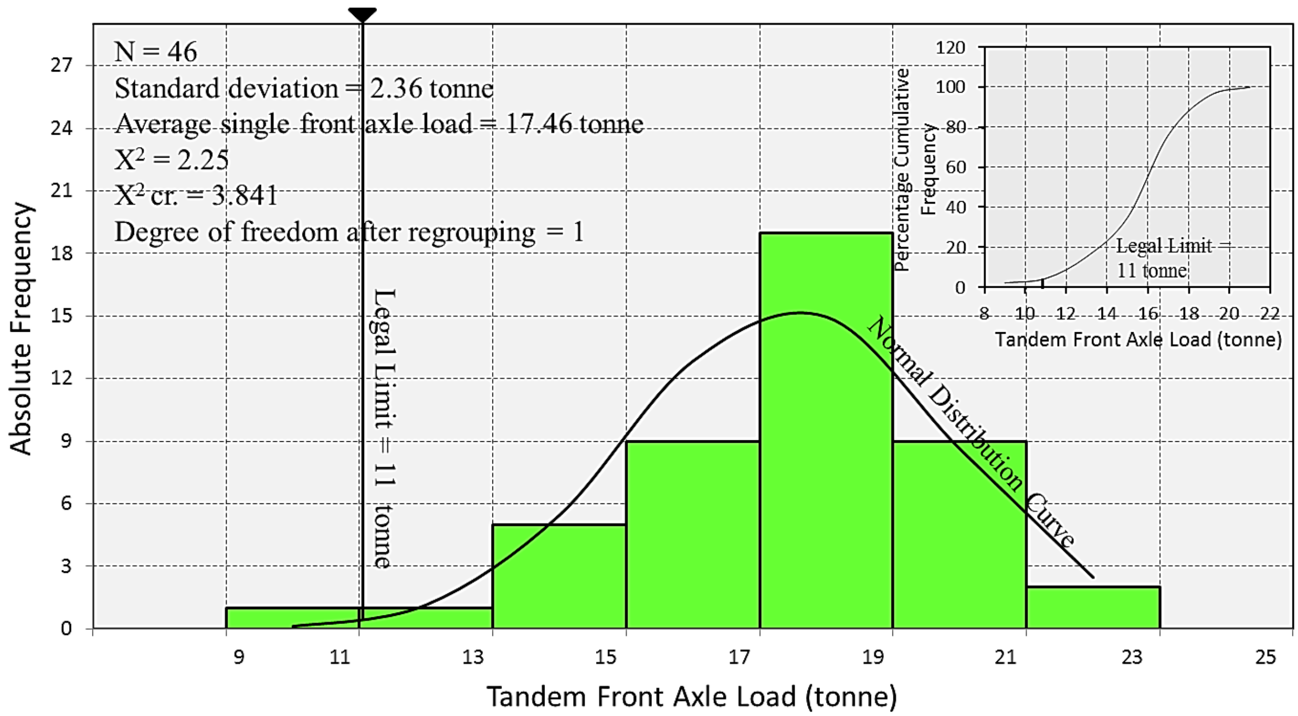


Fig. (3.6.a) Frequency distribution histogram of the front tandem axle load of tractor unit type (11.2).

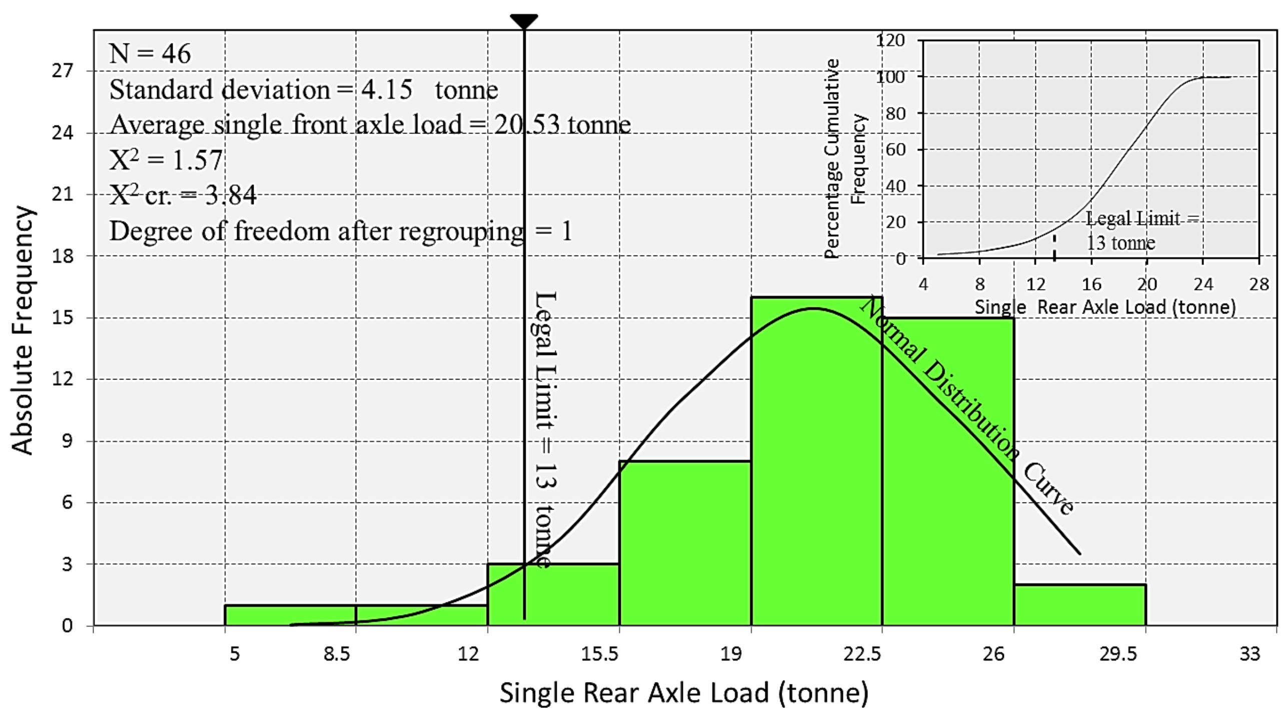


Fig. (3.6.b) Frequency distribution histogram of the rear single axle load of tractor unit type (11.2).

However, for tractor unit type (11.22), Figure (3.7.a) shows the frequency distribution histogram together with the normal distribution curve of front tandem axle load. The maximum front tandem axle load obtained from the survey of this study was 20.71 tonne (203.1 kN) much greater than the legal limit of 10 to 11 tonne (98.1 to 107.8 kN) according to Registration National Heavy Vehicle Reform, New South Wales (2001), and the distribution follows the normal distribution.

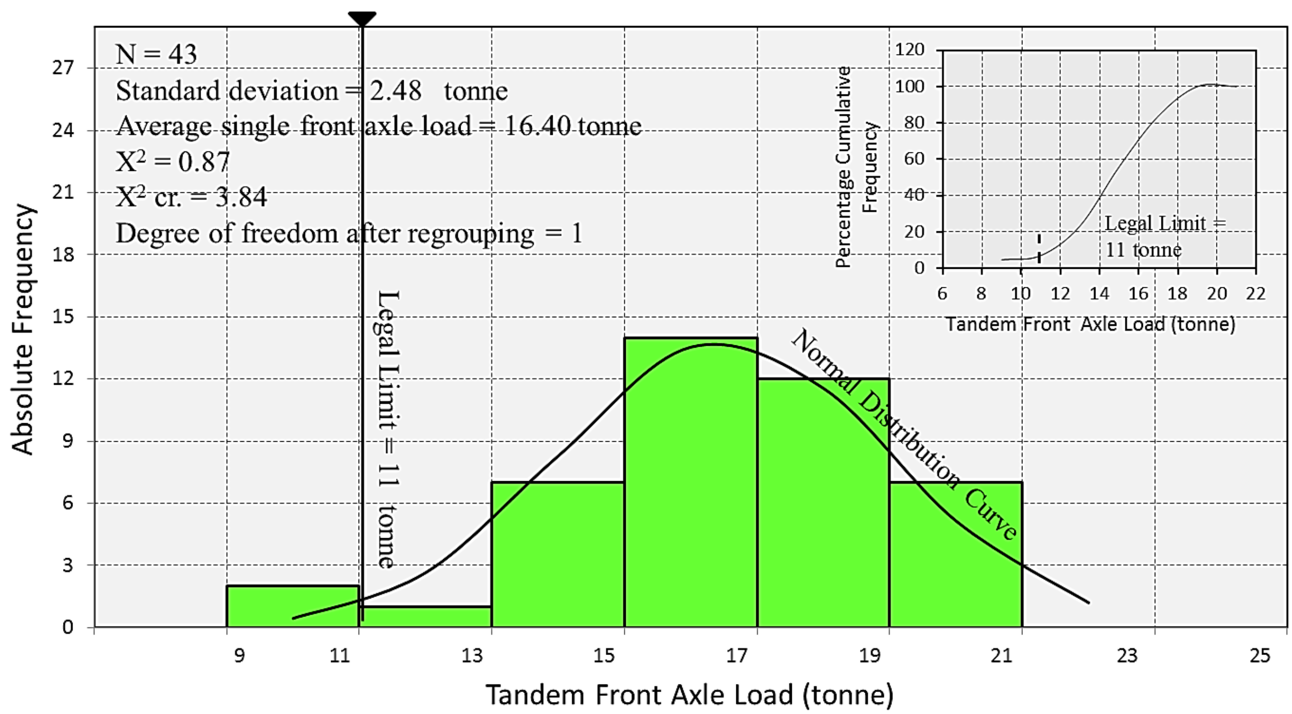


Fig. (3.7.a) Frequency distribution histogram of the front tandem axle load of tractor unit type (11.22).

Figure (3.7.b) shows the frequency distribution histogram of the rear tandem axle load of the tractor unit type (11.22). The maximum rear tandem axle load obtained from the survey of this study was 33.43 tonne (327.84 kN), which is greater than the legal limit of 20 tonne (196.13) according to SCRB (2009), and the distribution follows the normal distribution.

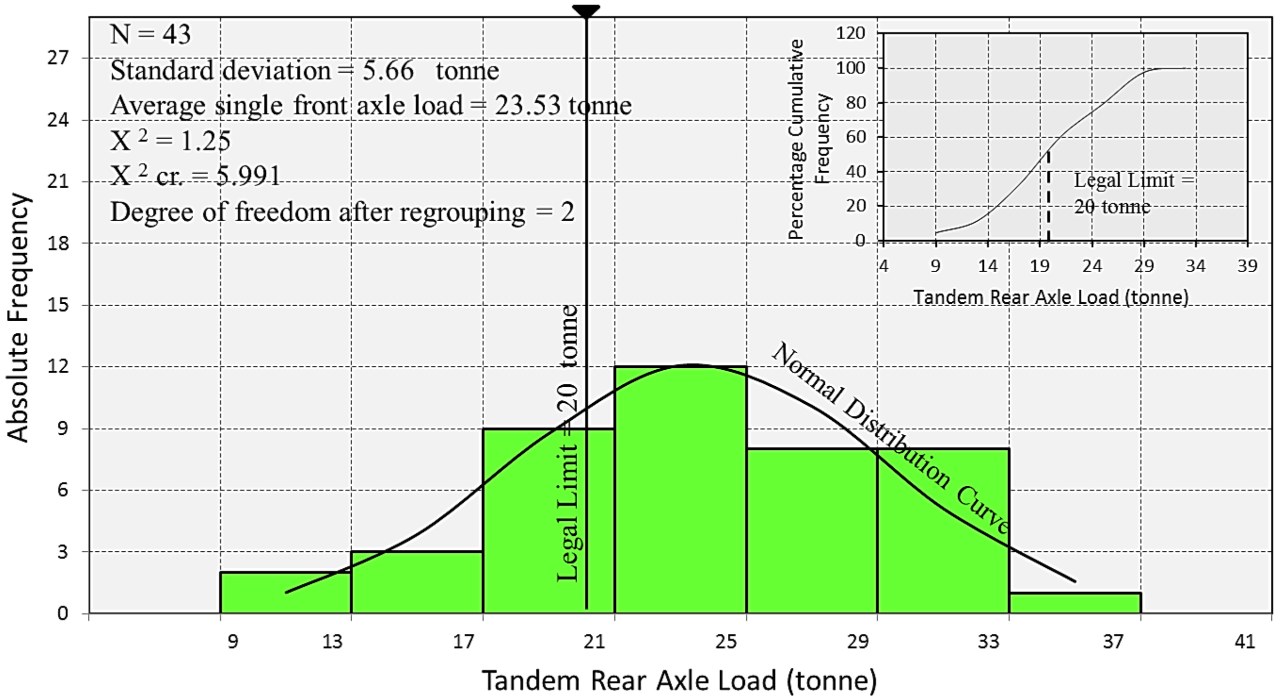


Fig. (3.7.b) Frequency distribution histogram of the rear tandem axle load of tractor unit type (11.22).

For trailer unit type (2.2), the chi-square goodness of fit test (Bluman, 2001), revealed that the hypothesis of normality is valid for both the front and rear axles of the tractor unit for a level of significance (α = 5%) as shown in Figure (3.8.a) and Figure (3.8.b), respectively.

It is obvious from Figure (3.8.a) that the maximum front tandem axle load of trailer unit type (2.2) obtained from the survey of this study was 14.07 tonne (137.98kN), which is close to the legal limit of 13 tonne (127.49 kN) according to SCRB (2009). However, from Figure (3.7.b), it is obvious that the maximum rear single axle load of tractor unit type (2.2) obtained from the survey of this study was 24.63 tonne (241.54 kN), which is much higher than the legal limit in Iraq of 13 tonne (127.49 kN) indicating serious overloading.

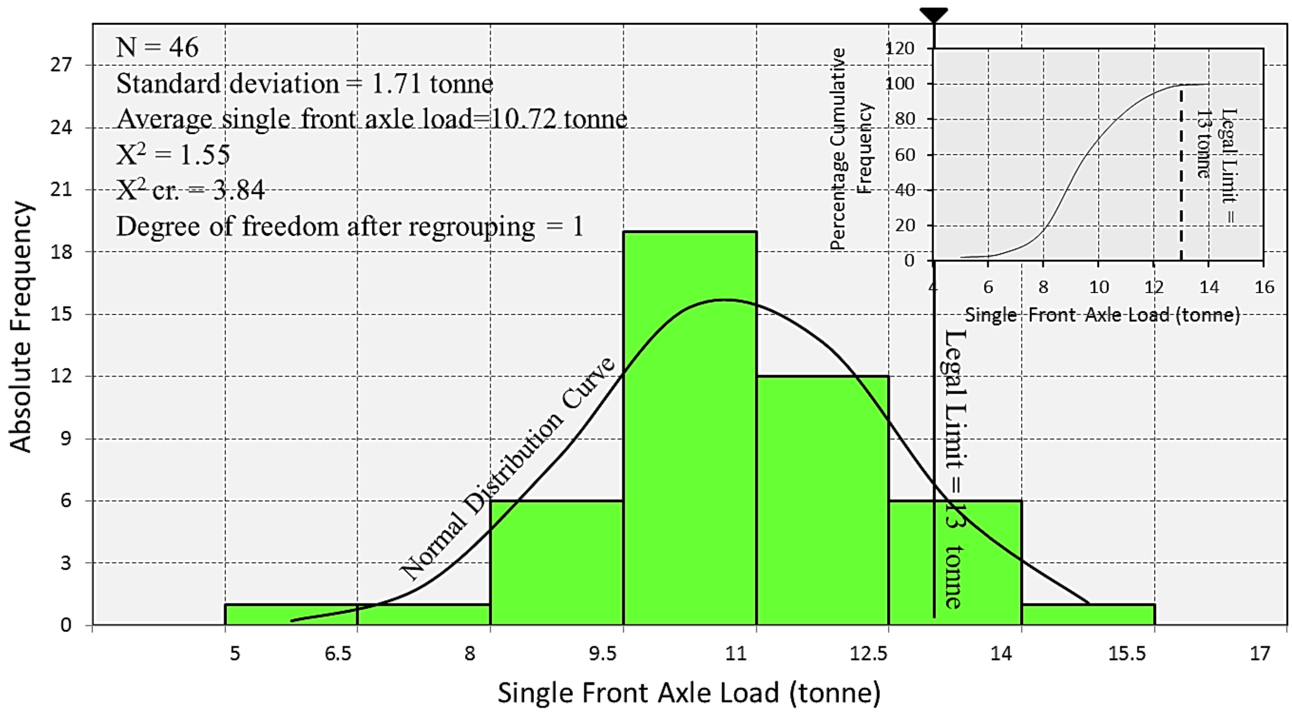


Fig. (3.8.a) Frequency distribution histogram of the front single axle load of trailer unit type (2.2).

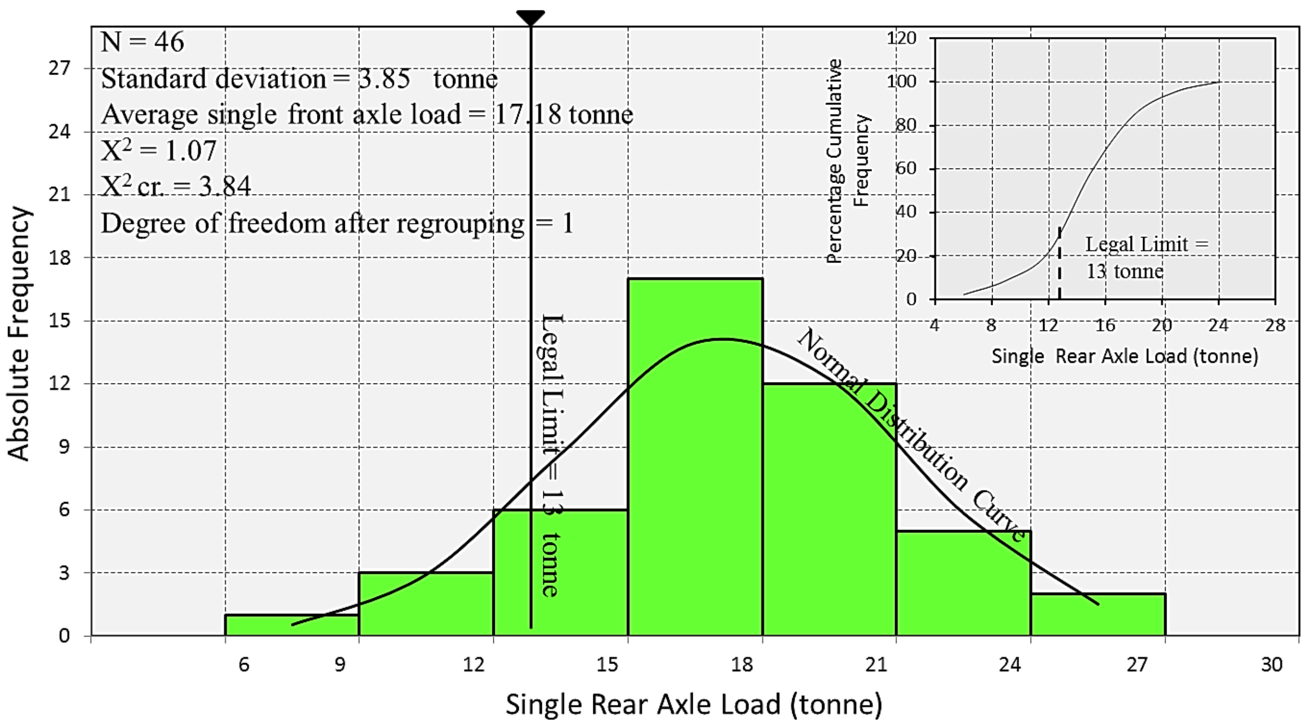


Fig. (3.8.b) Frequency distribution histogram of the rear single axle load of trailer unit type (2.2).

On the other hand, for trailer unit type (2.22), Figure (3.9.a) shows the front single axle load frequency distribution histogram. The maximum front single axle load obtained from the survey of this study was 14.16 tonne (138.86 kN), which is close to the legal limit of 13 tonne (127.49 kN), and the distribution follows the normal distribution.

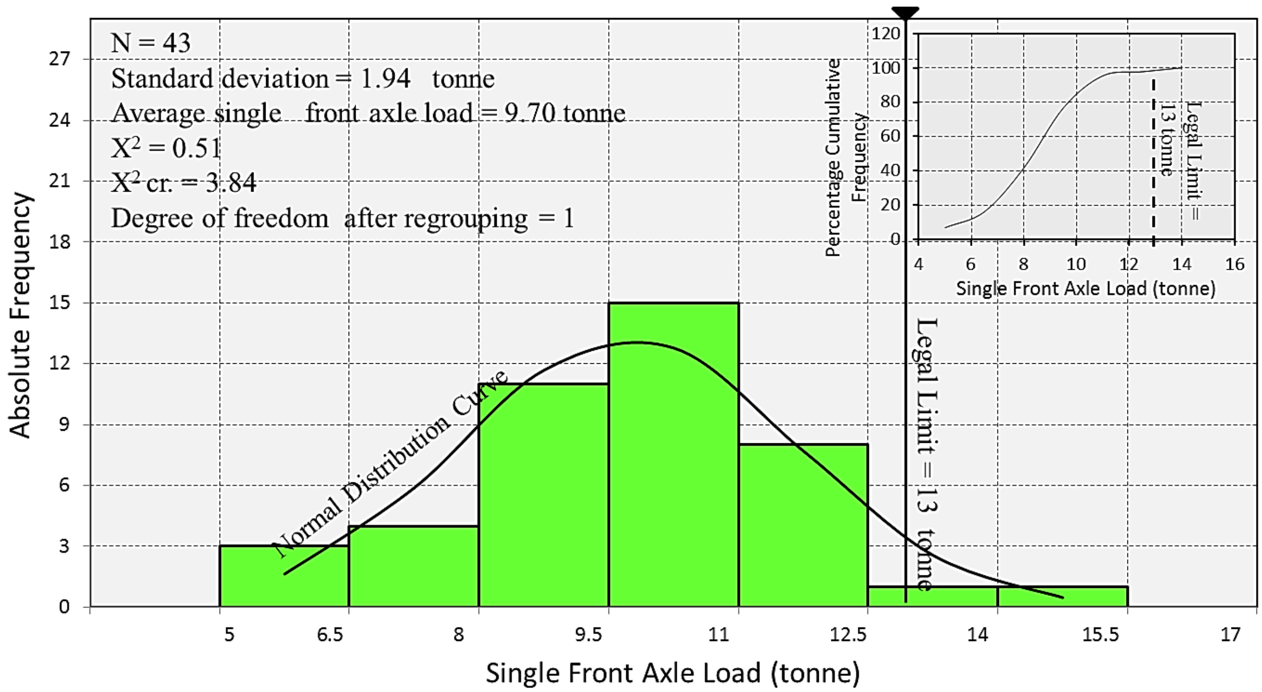


Fig. (3.9.a) Frequency distribution histogram of the front single axle load of trailer unit type (2.22).

Figure (3.9.b) shows the frequency distribution histogram for rear tandem axle load of trailer unit type (2.22).The maximum rear tandem axle load obtained from the survey of this study was 25.52 tonne (250.27 kN), which is greater than the legal limit of 20 tonne (196.13 kN), and the distribution follows the normal distribution.

Accordingly, it can be concluded that the phenomenon of overloading is quite obvious supporting the conclusions made by Al-Muhanna (2008).

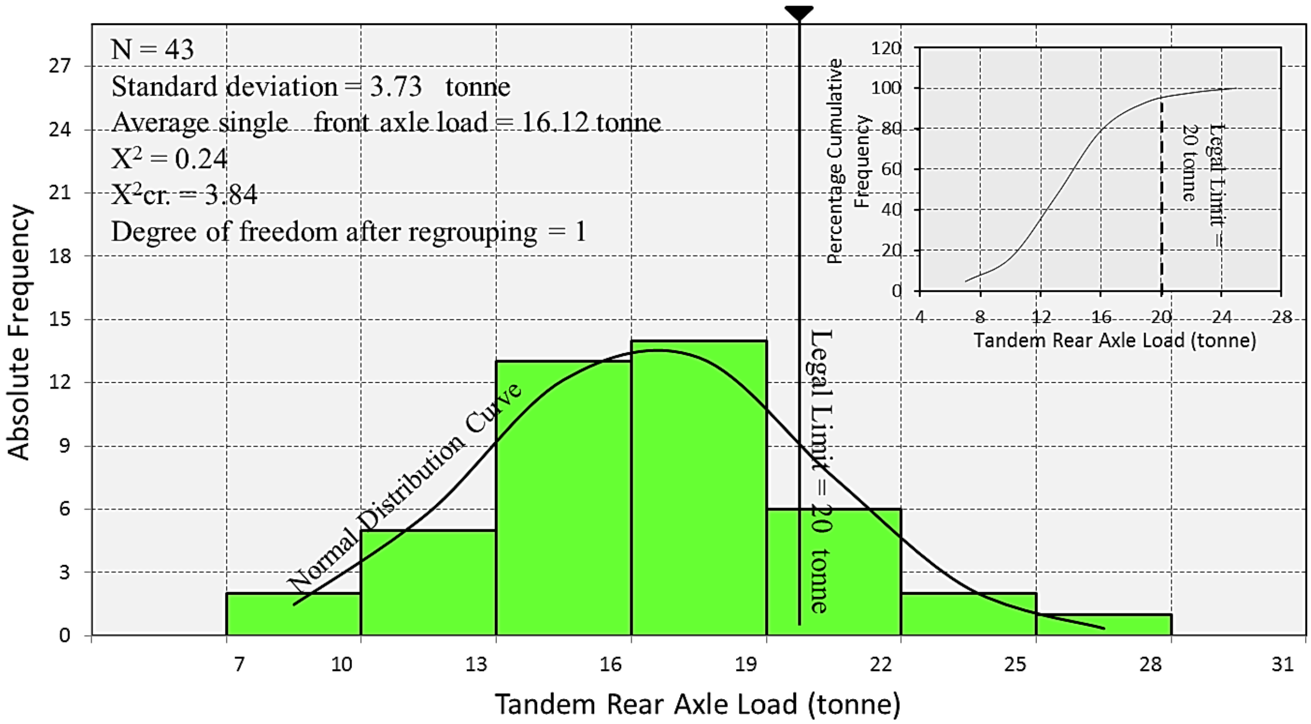


Fig. (3.9.b) Frequency distribution histogram of the rear tandem axle load of trailer unit type (2.22).

3.5.2 Ratio of Height of Center of Gravity to the Wheelbase of Full-Trailer Trucks

As mentioned before, the ratio of the height of the center of gravity to the wheelbase (H/B) is the most important factor affecting the truck equivalence factor on the uphill pavement.

For tractor unit type (11.2), Table (3.14) shows typical results of the axle geometry and vehicle dimensions (see Figure (3.2)).

For loaded trucks and to be on the safe side, the lower bound of the height of center of gravity may be taken as $(h_1+h_2)/2$ and $(h_3+h_4)/2$ for the tractor and trailer, respectively, while the upper bound was taken as h_2 or h_4 due to the phenomenon of overloading in the Middle East **(Pearson-Kirk, 1989)**.

Table (3.14) Typical results of the geometrical characteristics for 11.2 tractor unit.

B_1 (mm)	h_1 (mm)	h_2 (mm)	$(h_1+h_2)/2$ (mm)	H_1^*/B_1	
				Lower limit	Upper limit
5495	1398	2587	1993	0.36	0.47
4880	1280	2850	2065	0.42	0.58
4065	1280	2850	2065	0.51	0.70
2650	1300	2400	1850	0.70	0.91
2880	1320	3000	2160	0.75	1.04
			Average	0.55	0.74

*H_1= height of the center of gravity of the tractor unit above the pavement.
h1=Vertical distance measured from the top of the load container of tractor to the pavement, mm.
h2=Vertical distance measured from the bottom of load container of the tractor to the pavement, mm.
B1= Wheelbase length of tractor of full-trailer, mm.

For tractor unit type (11.22), Table (3.15) shows typical results of the axle geometry and vehicle dimensions (see Figure (3.2)).

Table (3.15) Typical results of the geometrical characteristics for 11.22 tractor unit.

B_1 (mm)	h_1 (mm)	h_2 (mm)	$(h_1+h_2)/2$ (mm)	H_1^*/B_1	
				Lower limit	Upper limit
5200	1300	2734	2017	0.39	0.53
4335	1356	2960	2158	0.50	0.68
3560	1340	3120	2230	0.63	0.88
3738	1460	3700	2580	0.69	0.99
2910	1400	3000	2200	0.76	1.03
			Average	0.59	0.82

*H_1= height of the center of gravity of the tractor unit above the pavement.
h1=Vertical distance measured from the top of the load container of tractor to the pavement, mm.
h2=Vertical distance measured from the bottom of load container of the tractor to the pavement, mm.
B1= Wheelbase length of tractor of full-trailer, mm.

However, for trailer unit type (2.2), Table (3.16) shows typical results of the axle geometry and vehicle dimensions (see Figure (3.2)).

Table (3.16) Typical results of the geometrical characteristics for 2.2 trailer unit.

B_2 (mm)	h_3 (mm)	h_4 (mm)	$(h_3+h_4)/2$ (mm)	H_2^*/B_2	
				Lower limit	Upper limit
5560	1255	2700	1978	0.36	0.49
5430	1499	3100	2299	0.42	0.57
4987	1539	3300	2419	0.49	0.66
3970	1299	2830	2065	0.52	0.71
3880	1600	3020	2310	0.60	0.78
			Average	0.47	0.63

*H_2= height of the center of gravity of the trailer unit above the pavement.
h3=Vertical distance measured from the top of the load container of trailer to the pavement, mm.
h4=Vertical distance measured from the bottom of load container of the trailer to the pavement, mm.
B_2= Wheelbase length of trailer of full-trailer, mm.

For trailer unit type (2.22), Table (3.17) shows typical results of the axle geometry and vehicle dimensions (see Figure (3.2)).

Table (3.17) Typical results of the geometrical characteristics for 2.22 trailer unit.

B_2 (mm)	h_3 (mm)	h_4 (mm)	$(h_3+h_4)/2$ (mm)	H_2^*/B_2	
				Lower limit	Upper limit
5390	1300	2800	2050	0.38	0.52
5205	1449	3200	2325	0.45	0.61
4990	1623	3333	2478	0.50	0.67
4200	1533	3280	2407	0.57	0.78
3990	1400	3690	2545	0.64	0.92
3240	1490	3480	2485	0.77	1.07
			Average	0.55	0.76

*H_2= height of the center of gravity of the trailer unit above the pavement.
h3=Vertical distance measured from the top of the load container of trailer to the pavement, mm.
h4=Vertical distance measured from the bottom of load container of the trailer to the pavement, mm.
B_2= Wheelbase length of trailer of full-trailer, mm.

For tractor type 11.2, the survey revealed that the wheelbase (B_1), which was calculated using equation (3.5), varied from 2650 mm to 5495 mm. However, for tractor type 11.22, the survey of this study revealed that the wheelbase (B_1) calculated using equation (3.6), varied from 2910 mm to 5200 mm.

On the other hand, for trailer unit type 2.2, the survey revealed that the wheelbase (B_2) varied from 3880 mm to 5560 mm, while the range for tractor type 2.22 (by using equation (3.7)) was from 3240 mm to 5390 mm.

It is quite obvious from Tables (3.13 through 3.16) that the H/B ratio for various tractor and trailer types varied between 0.36 and 1.07.

Al-Muhanna (2008) reported that the H/B ratio for various tractor and trailer types for full-trailer trucks type (1.2+2.2, 1.2+2.22, 1.22+2.2 and 1.22+2.22) varied between 0.35 and 1.0.

Razouki and Mohee (1999) reported in their survey that the range of H/B ratio was 0.2 to 1.0. Therefore, the ratio of H/B to be adopted in this study is in the range of 0.2 to 1.0 for both loaded and empty full-trailer trucks of all types.

4

CHAPTER FOUR

AASHTO LOAD EQUIVALENCY FACTORS FOR FULL-TRAILER TRUCKS ON UPHILL FLEXIBLE PAVEMENTS

CHAPTER FOUR

AASHTO LOAD EQUIVALENCY FACTORS FOR FULL- TRAILER TRUCKS ON UPHILL FLEXIBLE PAVEMENTS

4.1 General

Khisty and Lall (1998) pointed out that truck operating characteristics on uphill pavements are different from those on level pavements. The truck speeds are influenced greatly by uphill, and there is a decrease in truck speed by about 7% or more with the operation on a level section.

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. This difference in the damaging effect of axle loads resulting from uphill slopes will be reflected in the design of layers of flexible pavements.

4.2 Axle Load Distribution of Full-Trailer on Uphill Slope

As mentioned in previous Chapters, the distribution of axle loads of truck on uphill pavement differs from that on a level pavement.

To study the redistribution of axle loads of full-trailer trucks on uphill pavements, it is necessary to treat the following three cases for full-trailer trucks. The first case is that for no motion on a level highway representing the case of weighing to get the corresponding axle loads of full-trailers. The second case is that for uniform motion on a level highway, while the third case corresponds to the case of uniform motion on uphill pavements.

First Case (no motion on a level highway pavement)

For the case of no motion on a level highway pavement, it is assumed that:

1. The front tandem axle's load is equivalent to one force acting in the middle between the consecutive axles on each side.
2. The load is distributed equally over the wheels.

For this case, the analysis of the axle loads will be considered for each of the tractor and the trailer units as follows (see Figure (4.1)):

For the tractor unit

$$\mathbf{W_1 = F_{O1} + R_{O1}} \qquad \textbf{(4.1)}$$

$$\mathbf{B_1 = l_{11} + l_{12}} \qquad \textbf{(4.2)}$$

The front axle load of tractor unit can be obtained by taking the moments about the rear axle (point B in Figure (4.1)) as follows:

$$\mathbf{F_{O1} \times B_1 - W_1 \times l_{12} = 0}$$

or

$$\mathbf{F_{O1} = W_1 \times l_{12} / B_1} \qquad \textbf{(4.3)}$$

$$\mathbf{\therefore l_{12} = \frac{F_{O1}}{W_1} \times B_1 = \frac{F_{O1}}{(F_{O1} + R_{O1})} \times B_1} \qquad \textbf{(4.4)}$$

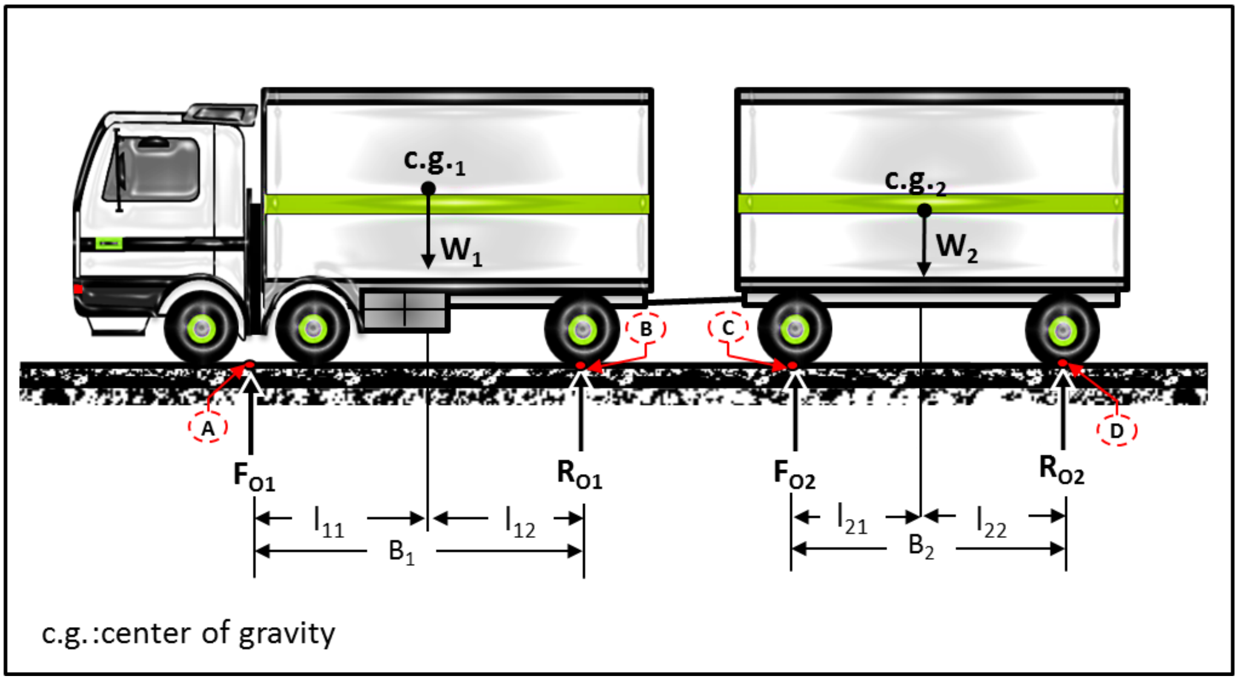


Fig. (4.1) Axle loads of full-trailer on a level road (no motion).

Similarly, the sum of moments about the front axle of tractor unit (point A in Figure (4.1)) yields:

$$\mathbf{R_{O1} \times B_1 - W_1 \times l_{11} = 0}$$

or

$$\mathbf{R_{O1} = W_1 \times {}^{l_{11}}\!/\!{}_{B_1}} \qquad \textbf{(4.5)}$$

$$\therefore \mathbf{l_{11} = \frac{R_{O1}}{W_1} \times B_1 = \frac{R_{O1}}{(F_{O1} + R_{O1})} \times B_1} \qquad \textbf{(4.6)}$$

<u>For the trailer unit</u>

$$\mathbf{W_2 = F_{O2} + R_{O2}} \qquad \textbf{(4.7)}$$

$$\mathbf{B_2 = l_{21} + l_{22}} \qquad \textbf{(4.8)}$$

For trailer unit as shown in Figure (4.1), the front axle load can be obtained by taking the moments about the rear axle (point D in Figure (4.1)) as follows:

$$\mathbf{F_{O2} \times B_2 - W_2 \times l_{22} = 0}$$

or

$$F_{O2} = W_2 \times {l_{22}}/{B_2} \tag{4.9}$$

$$\therefore l_{22} = \frac{F_{O2}}{W_2} \times B_2 = \frac{F_{O2}}{(F_{O2} + R_{O2})} \times B_2 \tag{4.10}$$

Similarly, the sum of moments about the front axle of trailer unit (point C in Figure (4.1)) yields:

$$R_{O2} \times B_2 - W_2 \times l_{21} = 0$$

or

$$R_{O2} = W_2 \times {l_{21}}/{B_2} \tag{4.11}$$

$$\therefore l_{21} = \frac{R_{O2}}{W_2} \times B_2 = \frac{R_{O2}}{(F_{O2} + R_{O2})} \times B_2 \tag{4.12}$$

where:

B_1, B_2 = wheelbase lengths for the tractor and trailer units, respectively.

l_{11}, l_{12} = distances from the center of gravity of tractor to its front and rear axles, respectively.

l_{21}, l_{22} = distances from the center of gravity of trailer unit to its front and rear axles, respectively.

F_{O1}, R_{O1} = front and rear axle loads for tractor unit on a level surface.

F_{O2}, R_{O2} = front and rear axle loads for trailer unit on a level surface.

W_1, W_2 = total weights of the tractor and trailer units, respectively.

<u>Second Case (Uniform motion on a level road)</u>

For case of uniform motion on a level highway pavement, it is assumed that:

1. The front tandem axle’s load is equivalent to one force acting in the middle between the consecutive axles on each side.
2. The load distributed equally over the wheels.

3. There is no vibration perpendicular to the pavement during uniform motion on level.

In this case, the pull force between the tractor and trailer has an impact on the redistribution of axle loads. The equations of equilibrium can be applied because of zero inertia forces.

As mentioned previously, the pull force (T_O) between the tractor and the trailer can be obtained from the equation of regression analysis for the data obtained from Al-Muhanna (2008) survey as given by equation (3.9), which is repeated below for convenience.

$$\mathbf{To = 0.0008 \times \left(W_2 \right)^{1.5433}}$$

It is quite obvious from this equation that the pull force between the tractor and the trailer on a level road for uniform motion is related directly to the weight of the trailer unit. This equation was derived for trailer units having weights ranging from 74 kN to 463 kN

<u>For the tractor unit</u>

For tractor unit as shown in Figure (4.2), the front axle load can be obtained by taking the moments about the rear axle (point B in Figure (4.2)) as follows:

$$\mathbf{F_{L1} \times B_1 + T_O \times E - W_1 \times l_{12} = 0}$$

or

$$\mathbf{F_{L1} = W_1 \times {l_{12}}/{B_1} - T_O \times {E}/{B_1}} \qquad \textbf{(4.13)}$$

The substitution of equation (4.3) into equation (4.13) yields:

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$$F_{L1} = F_{O1} - T_O \times {E}/{B_1} \qquad (4.14)$$

Similarly, the sum of moments about the front axle of tractor unit (point A in Figure (4.2)) yields:

$$R_{L1} \times B_1 - T_O \times E - W_1 \times l_{11} = 0$$

or

$$R_{L1} = W_1 \times {l_{11}}/{B_1} + T_O \times {E}/{B_1} \qquad (4.15)$$

The substitution of equation (4.5) into equation (4.15) yields:

$$R_{L1} = R_{O1} + T_O \times {E}/{B_1} \qquad (4.16)$$

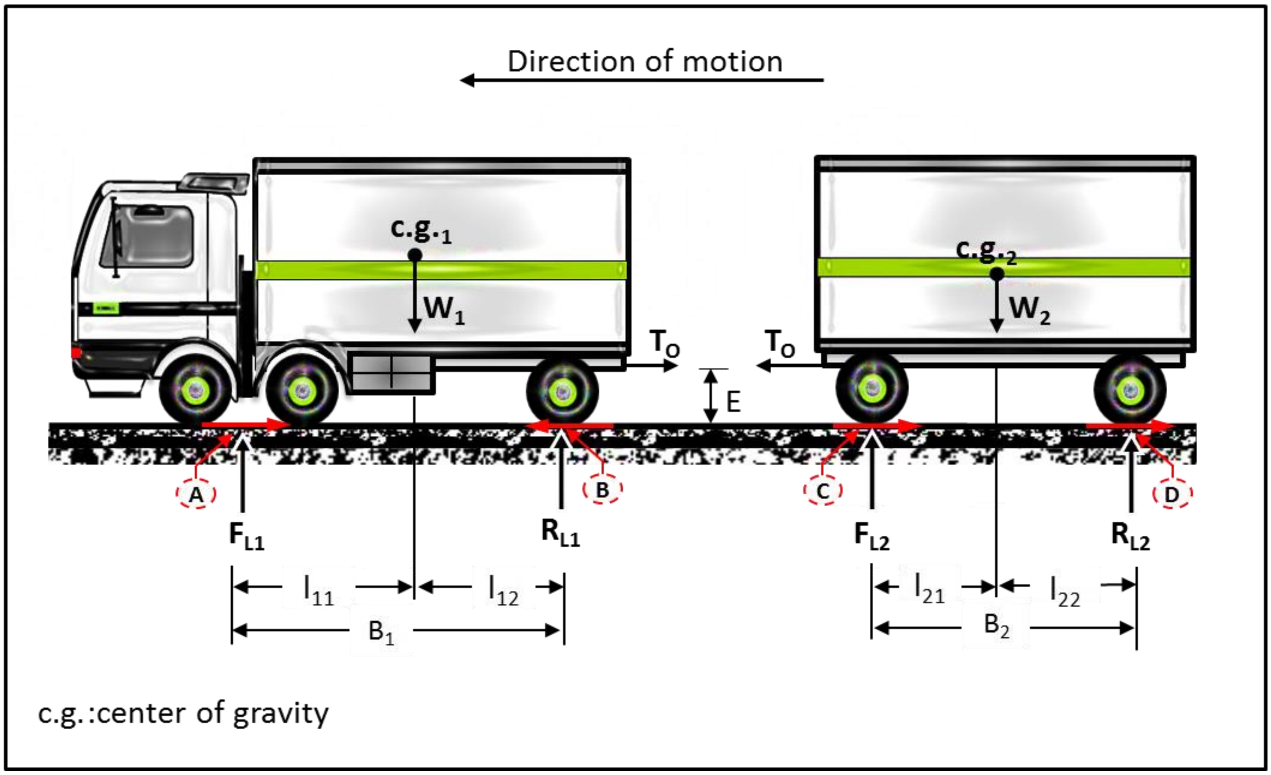

Fig. (4.2) Axle loads of full-trailer moving with uniform motion on a level road.

For the trailer unit

For trailer unit as shown in Figure (4.2), the front axle load of trailer unit can be obtained by taking the moments about the rear axle (point D in Figure (4.2)) as follows:

$$\mathbf{F_{L2} \times B_2 - T_O \times E - W_2 \times l_{22} = 0}$$

or

$$\mathbf{F_{L2} = W_2 \times {l_{22}}/{B_2} + T_O \times {E}/{B_2}} \qquad \textbf{(4.17)}$$

The substitution of equation (4.9) into equation (4.17) yields:

$$\mathbf{F_{L2} = F_{O2} + T_O \times {E}/{B_2}} \qquad \textbf{(4.18)}$$

Similarly, the sum of moments about the front axle of trailer unit (point C in Figure (4.2)) yields

$$\mathbf{R_{L2} \times B_2 + T_O \times E - W_2 \times l_{21} = 0}$$

or

$$\mathbf{R_{L2} = W_2 \times {l_{21}}/{B_2} - T_O \times {E}/{B_2}} \qquad \textbf{(4.19)}$$

The substitution of equation (4.11) into equation (4.19) yields:

$$\mathbf{R_{L2} = R_{O2} - T_O \times {E}/{B_2}} \qquad \textbf{(4.20)}$$

where:

$\mathbf{T_O}$= pull force between the tractor and the trailer unit for the case of uniform motion on a level highway.

E = height of the pull force above the pavement.

$\mathbf{F_{L1}}$, $\mathbf{R_{L1}}$ = front and rear axle loads for the tractor unit on a level road during uniform motion.

F_{L2}, R_{L2} = front and rear axle loads for the trailer unit on a level road during uniform motion.

E = Height of the pull force above the pavement.

Equations (4.14) and (4.16) reveal that the pull force (T_O) between the tractor and trailer unit causes a decrease in front axle load of the tractor unit and an increase in its rear axle load. However, equations (4.17) and (4.20) show the opposite of this phenomenon for the trailer unit.

Third Case (Uniform motion on uphill)

For case of uniform motion on an uphill highway pavement, it is assumed that:

1. The front tandem axle's load is equivalent to one force acting in the middle between the consecutive axles on each side.
2. The load distributed equally over the wheels.
3. There is no vibration perpendicular to the pavement during uniform motion on uphill pavement.

On the 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 Figure (4.3)). As reported by Al-Muhanna (2008), it was not possible to measure the pull force for the case of uniform motion of full-trailer on the uphill slopes. Thus, it was reported that the same equation of the pull force on the level road would be taken on the uphill slope but after multiplying the weight (W_2) by ($\cos\theta$) and

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adding to this equation the component of the weight of the trailer unit parallel to the uphill pavement as follows:

$$\mathbf{T = 0.0008 \times \left(W_2 \times \cos\theta\right)^{1.5433} + W_2 \times \sin\theta} \qquad \textbf{(4.21)}$$

When applying Θ = 0 to equation (4.21), T returns to T_O (the case of a level road).

As mentioned in chapter two, the vehicle is subjected to three resistances while it is moving on a straight line. These are rolling resistance, gradient resistance and aerodynamic resistance. If a vehicle has to start moving, it has to generate enough tractive force at the wheels to exceed these resistances. Since a vehicle should be ready to be driven on all types of terrains, tractive effort and tire grip become the deciding factors. Engine's tractive force is in continuous development, therefore, this study will take into consideration a maximum upgrade of 18% that is obtained from a previous survey.

For the tractor unit

For the tractor unit shown in Figure (4.3), the front axle load can be obtained by taking the moments about the rear axle (point B in Figure (4.3)) of the tractor unit as follows:

$$\mathbf{F_{G1} \times B_1 - W_1 \times \cos\theta \times l_{12} + W_1 \times \sin\theta \times H_1 + T \times E = 0}$$

or

$$\mathbf{F_{G1} = W_1 \times \cos\theta \times {}^{l_{12}}\!/_{B_1} - W_1 \times \sin\theta \times {}^{H_1}\!/_{B_1} - T \times {}^{E}\!/_{B_1}} \qquad \textbf{(4.22)}$$

The substitution of equation (4.3) into equation (4.22) yields:-

$$\mathbf{F_{G1} = F_{O1} \times \cos\theta - W_1 \times \sin\theta \times {}^{H_1}\!/_{B_1} - T \times {}^{E}\!/_{B_1}} \qquad \textbf{(4.23)}$$

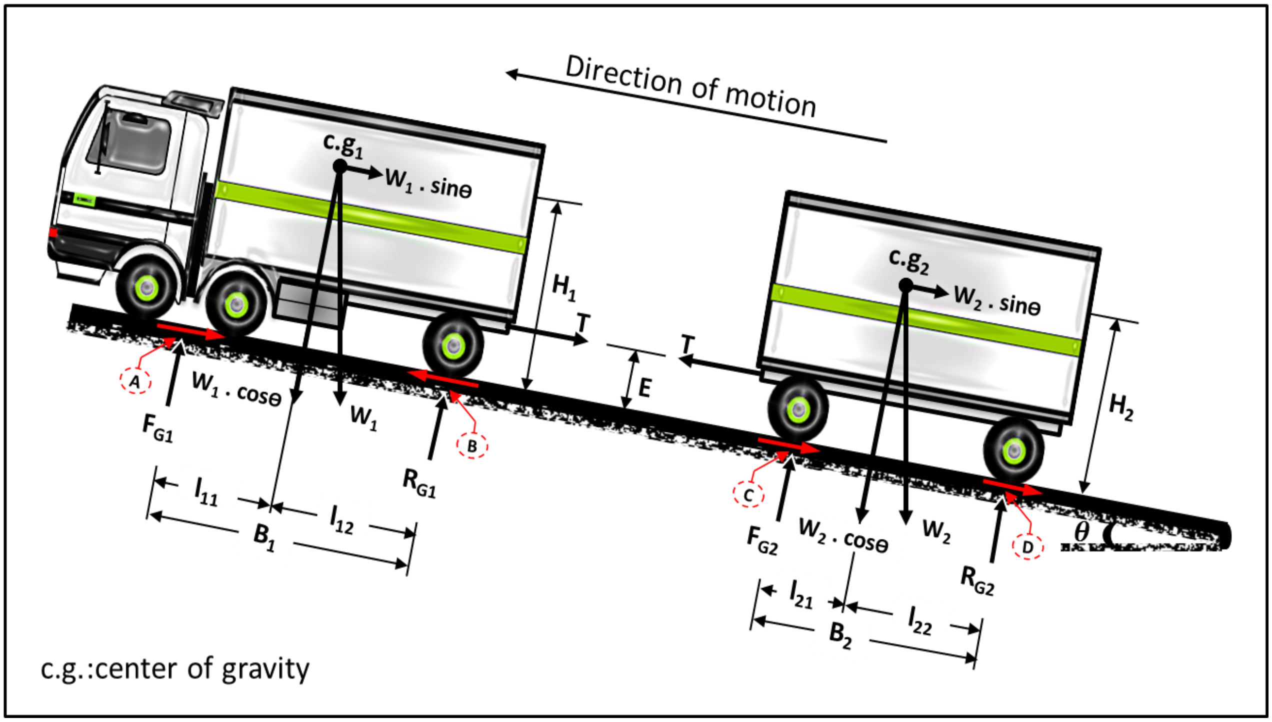

Fig. (4.3) Axle loads of full-trailer moving on an uphill pavement with uniform motion.

Similarly, the sum of moments about the front axle of tractor unit (point A in Figure (4.3)) yields:

$$\mathbf{R_{G1} \times B_1 - W_1 \times \cos\theta \times l_{11} - W_1 \times \sin\theta \times H_1 - T \times E = 0}$$

or

$$\mathbf{R_{G1} = W_1 \times \cos\theta \times {}^{l_{11}}\!/_{B_1} + W_1 \times \sin\theta \times {}^{H_1}\!/_{B_1} + T \times {}^{E}\!/_{B_1}} \qquad \mathbf{(4.24)}$$

The substitution of equation (4.5) into equation (4.24) yields:

$$\mathbf{R_{G1} = R_{O1} \times \cos\theta + W_1 \times \sin\theta \times {}^{H_1}\!/_{B_1} + T \times {}^{E}\!/_{B_1}} \qquad \mathbf{(4.25)}$$

For the trailer unit

For the trailer unit shown in Figure (4.3), the front axle load can be obtained by taking the moments about the rear axle (point D in Figure (4.3)) of the trailer unit as follows:

$$\mathbf{F_{G2} \times B_2 + W_2 \times \sin\theta \times H_2 - W_2 \times \cos\theta \times l_{22} - T \times E = 0}$$

or

$$\mathbf{F_{G2} = W_2 \times \cos\theta \times {}^{l_{22}}/_{B_2} - W_2 \times \sin\theta \times {}^{H_2}/_{B_2} + T \times {}^{E}/_{B_2}} \qquad \mathbf{(4.26)}$$

The substitution of equation (4.9) into equation (4.26) yields:

$$\mathbf{F_{G2} = F_{O2} \times \cos\theta - W_2 \times \sin\theta \times {}^{H_2}/_{B_2} + T \times {}^{E}/_{B_2}} \qquad \mathbf{(4.27)}$$

Similarly, the sum of moments about the front axle (point C in Figure (4.3)) of trailer unit yields:

$$\mathbf{R_{G2} \times B_2 - W_2 \times \cos\theta \times l_{21} - W_2 \times \sin\theta \times H_2 + T \times E = 0}$$

or

$$\mathbf{R_{G2} = W_2 \times \cos\theta \times {}^{l_{21}}/_{B_2} + W_2 \times \sin\theta \times {}^{H_2}/_{B_2} - T \times {}^{E}/_{B_2}} \qquad \mathbf{(4.28)}$$

The substitution of equation (4.11) into equation (4.28) yields:-

$$\mathbf{R_{G2} = R_{O2} \times \cos\theta + W_2 \times \sin\theta \times {}^{H_2}/_{B_2} - T \times {}^{E}/_{B_2}} \qquad \mathbf{(4.29)}$$

where:

F_{G1}, R_{G1} = front and rear axle loads for a tractor on upgrade.

F_{G2}, R_{G2} = front and rear axle loads for a trailer unit on upgrade.

Θ = angle of slope, tan (Θ) =grade.

H_1, H_2 = heights (above and perpendicular to the pavement) of the center of gravity for the tractor and the trailer unit, respectively.

E = Height of the pull force above the pavement.

4.3 <u>Determination of Axle Load Equivalency Factors</u>

As mentioned previously, the deterioration of paved roads caused by traffic is due to both the magnitude of the individual wheel (or axle) loads and the number of times these loads are applied. These factors are considered in pavement design in terms of load equivalency factors (LEF). These factors developed in the late 1950's by engineers analyzing data from AASHO Road Test. As mentioned in chapter two, the AASHTO load equivalency factor represents the ratio of a number of repetitions of 18 kips (80 kN) standard single axle load necessary to cause the same reduction in (PSI) as one application of any axle load and axle configuration (single, tandem, or triple).

Equation (2.4) was recommended by the AASHTO Guide for the design of pavement structures (AASHTO, 1986) to determine the EALF for flexible pavements.

In this study, the EALF should be determined for uphill flexible pavements. For this purpose, the same equations of AASHTO (1986) are to be used but in connection with the axle loads on the uphill pavement (i.e. after axle load redistribution) derived in section (4.2).

4.4 <u>Truck Equivalency Factors</u>

The effect of axle loadings to be used in the design of flexible highway pavements can be expressed in terms of truck equivalence factors (TEF).

As mentioned before, the truck equivalence factor is the number of equivalent standard 18 kips (80kN) single axle load repetitions corresponding to a given truck. By using the equations previously mentioned in Chapter two (see equation (2.4)), the equivalency factor for each axle type can be calculated. The summation of equivalence factors for axles of a particular vehicle is termed the truck equivalence factor, which can be calculated as previously mentioned in chapter two (see 2.5). Then, the average truck equivalence factor (Ta) can be calculated as follows:

$$\mathbf{T_a = \frac{\sum_{j=1}^{n}\left(T_{ej}\right)}{n}} \qquad \textbf{(4.30)}$$

where:

$\mathbf{T_{ej}}$ = Truck equivalency factor for j^{th} truck (j^{th} full-trailer).

n = Total number of Full Trailers of type 1.2+2.2, 1.2+2.22, 1.22+2.2, 1.22+2.22, 11.2+2.2 or 11.22+2.22.

The average truck equivalence factor can describe the damaging effect of each type of the trucks with different axle loads.

For this purpose, a computer program called FEFUF (Full-trailer Equivalence Factor for Uphill Flexible pavements) was written in MATLAB as shown in Appendix E and discussed below.

4.5 Computer Program for Determining Full-Trailer Truck Equivalency Factors for Uphill Flexible Pavements

The computer program FEFUF with the flow chart shown in Figure (4.4) was developed for determining the truck equivalency factors for full-trailers trucks of type 1.2+2.2, 1.2+2.22, 1.22+2.2, 1.22+2.22, 11.2+2.2, and 11.22+2.22.

The input data to the FEFUF program involves the structural number (SN) and the terminal level of serviceability (p_t) of the flexible pavement, magnitude of uphill slope, ratio of height of center of gravity (H) to the wheelbase (B) assuming that the ratio of height of center of gravity for each of the tractor and trailer to the corresponding wheelbase is the same, the total number (n) of full-trailer trucks of type (K) to be studied, and K.

The height of the pull force above the pavement (E) for all types of full-trailer trucks as mentioned before is constant and equal to 100 cm.

For each full-trailer, the next input data to the FEFUF program involves the measured front and rear axle loads (F_{O1} and R_{O1}, respectively) of tractor unit on a level pavement, and the measured front and rear axle loads (F_{O2} and R_{O2}, respectively) of trailer unit on a level pavement. In addition, the program requires the input of the wheelbase for each of tractor and trailer unit (B_1 and B_2, respectively).

After that, the computer program calculates the weight of the tractor and trailer unit by using equations (4.1) and (4.7) respectively. Then, it calculates the pull force between the tractor and trailer unit on uphill pavements using equation (3.9).

After that, the front axle load F_{G1} , the rear axle load R_{G1} of the tractor unit, the front axle load F_{G2} and the rear axle load R_{G2} of the trailer unit on uphill pavement are determined by using equations (4.23), (4.25), (4.27), and (4.29), respectively. Then, the equivalency factor for each of the front and rear axle of the tractor unit and each of the front and rear axle of the trailer unit are determined using equation (2.4) by considering that the F_{G1} and F_{G2} are the axle loads for the front axles and R_{G1} and R_{G2} are the axle loads for the rear axles of the truck.

By summing up the equivalency factors for the front and rear axles of the tractor unit and the front and rear axles of the trailer unit, the truck equivalency factor (T_{ej}) for the j^{th} full-trailer, is obtained. This process repeats itself for all n trucks of full-trailer type K.

Finally, for the same uphill slope, same structural number (SN), same H/B ratio, and same terminal level of serviceability (p_t), the average full-trailer truck equivalency factor (T_a) for each full-trailer type is obtained by using equation (4.30).

The output of the program FEFUF for each full-trailer type is the axle loads equivalency factors (E_i), the truck equivalency factors (T_e) and the average truck equivalency factor (T_a). Table (4.1) shows a typical output for the case of 1.2+2.2 full-trailer truck for H/B=1.0, structural number SN=4, uphill slope of 18% and p_t=2.5.

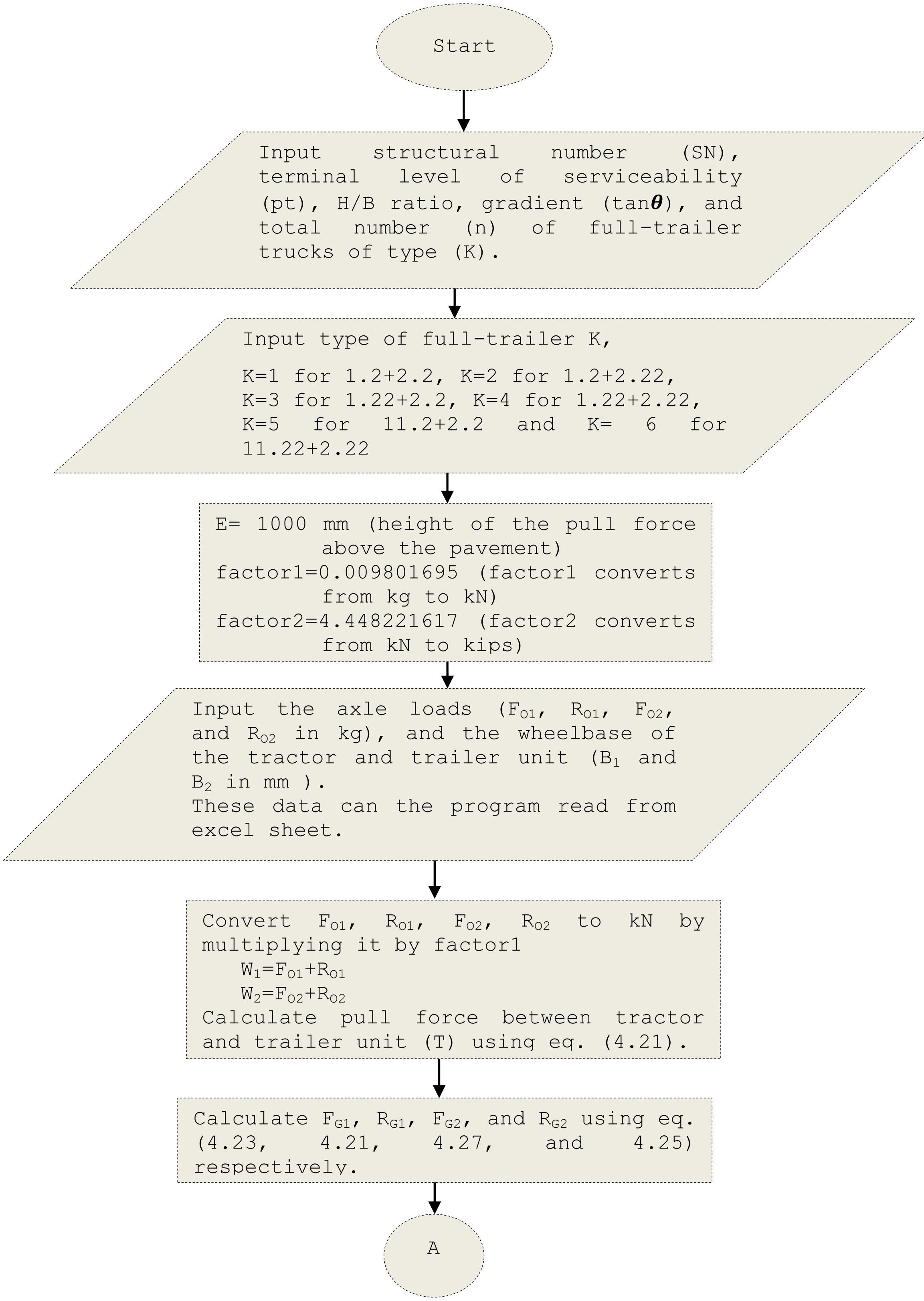

Fig. (4.4) Flow chart for FEFUF program.

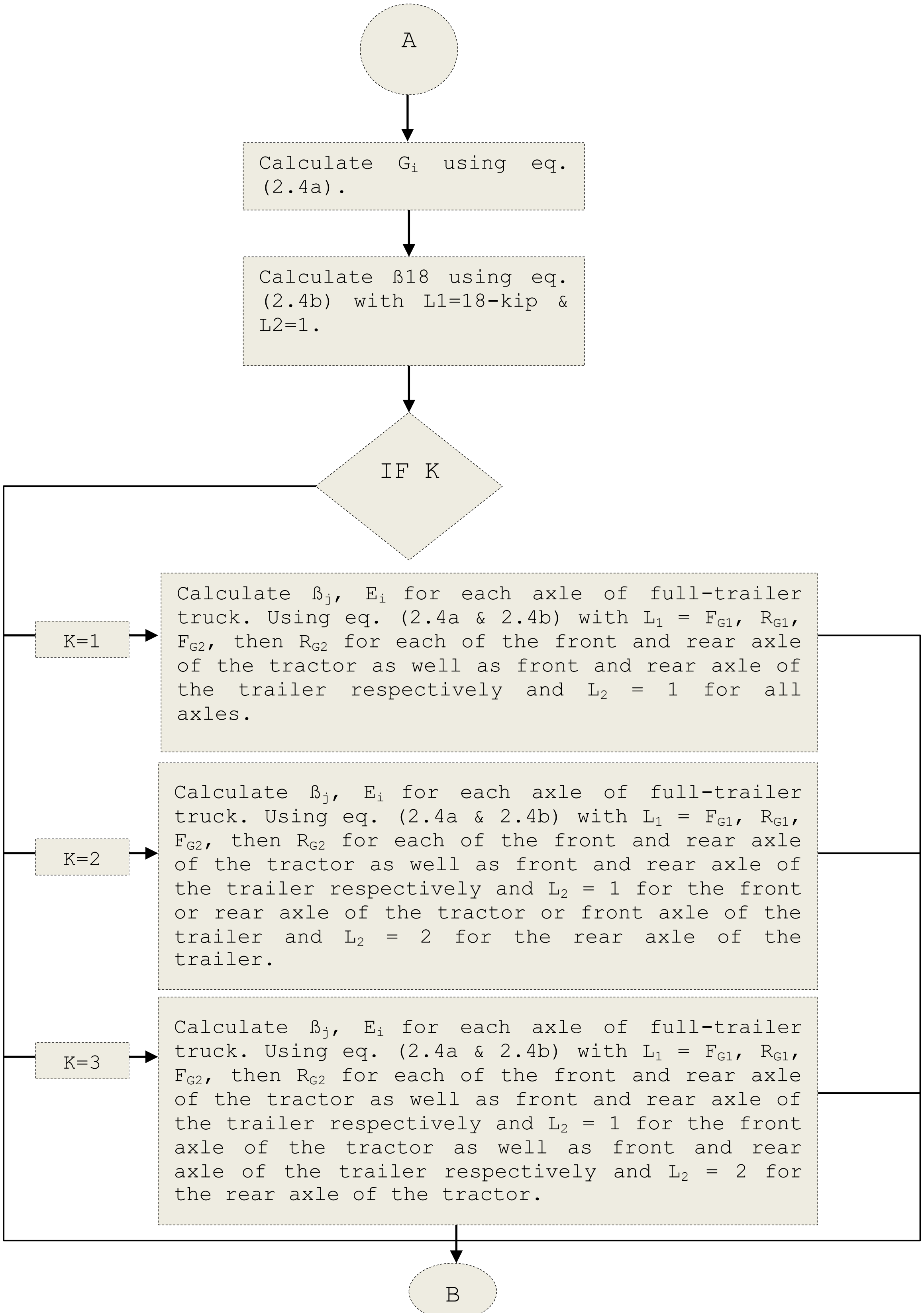

Fig. (4.4) Flow chart for FEFUF program, continued.

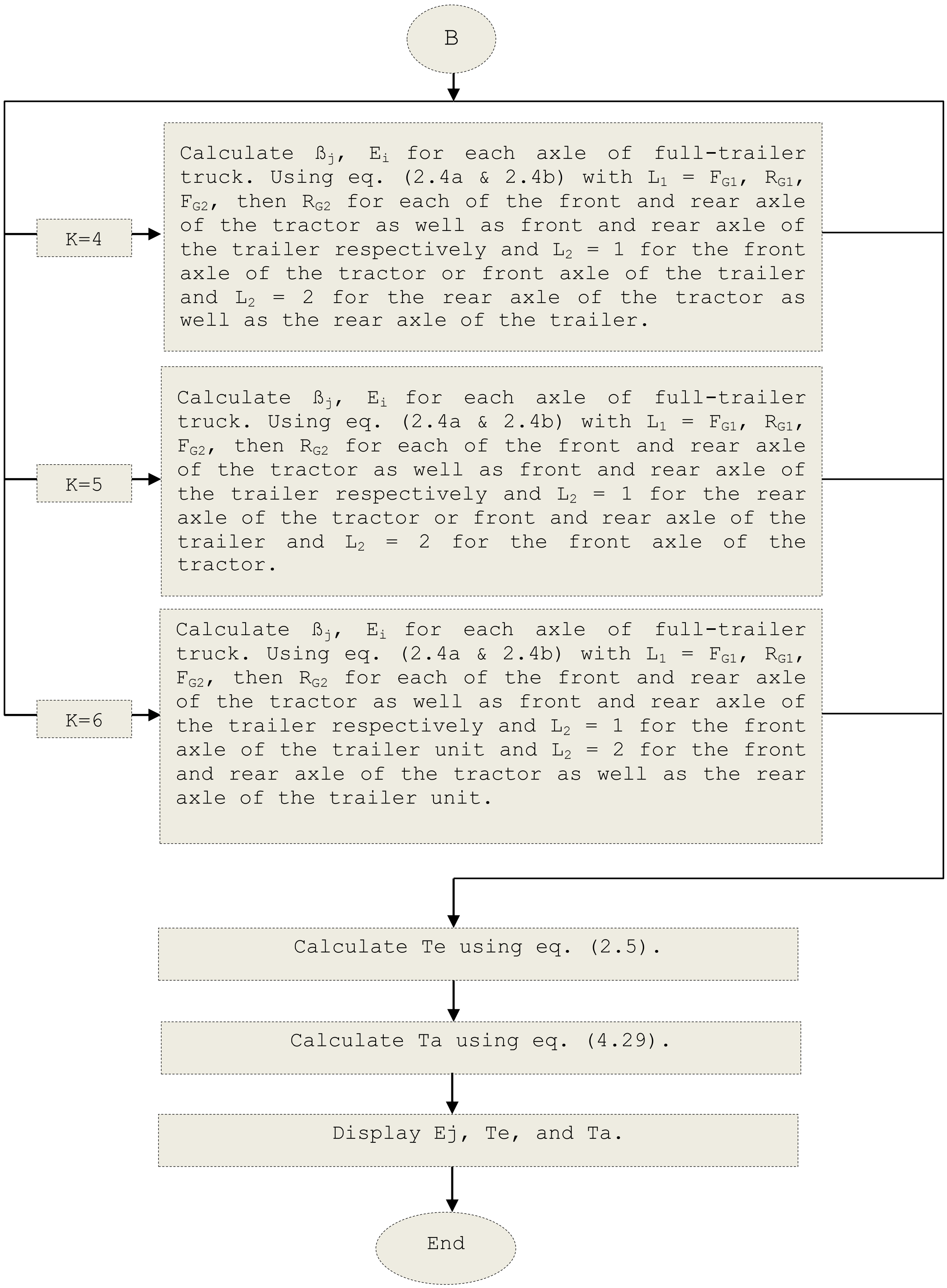

Fig. (4.4) Flow chart for FEFUF program, continued.

Table (4.1) Typical output of FEFUF program for the case of 1.2+2.2 full-trailer truck for H/B=1.0, structural number SN=4, uphill slope of 18% and p_t=2.5.

Truck number	Axle Type	Axle load on uphill pavement (kN)	Equivalency Factor on uphill slope (E_i)	Total weight of full-trailer (kN)	T_e
1	S.A.S	12.68049	0.0007	219.3652	3.4340
	S.A	105.9735	2.8145		
	S.A	31.04525	0.0236		
	S.A	69.66593	0.5952		
2	S.A.S	17.39818	0.0024	301.1689	8.7023
	S.A	130.5817	6.2686		
	S.A	53.87515	0.2205		
	S.A	99.31389	2.2108		
3	S.A.S	17.16063	0.0023	339.9485	16.8240
	S.A	157.8299	13.5324		
	S.A	57.03537	0.2759		
	S.A	107.9226	3.0134		
4	S.A.S	16.5847	0.0020	385.6737	30.6611
	S.A	182.9083	25.3424		
	S.A	63.59799	0.4209		
	S.A	122.5826	4.8958		
5	S.A.S	20.0740	0.0041	414.4208	43.1926
	S.A	198.7124	36.3983		
	S.A	64.66977	0.4487		
	S.A	130.9646	6.3415		
6	S.A.S	20.5338	0.0045	465.3551	75.0546
	S.A	226.2279	64.8600		
	S.A	73.94581	0.7443		
	S.A	144.6476	9.4458		
7	S.A.S	25.45211	0.0106	491.7869	91.7897
	S.A	236.7442	79.6270		
	S.A	78.76299	0.9410		
	S.A	150.8276	11.2110		
8	S.A.S	24.60882	0.0092	507.0288	112.0423
	S.A	248.1989	98.6842		
	S.A	79.78623	0.9871		
	S.A	154.4348	12.3617		

Table (4.1) Typical output of FEFUF program for the case of 1.2+2.2 full-trailer truck for H/B=1.0, structural number SN=4, uphill slope of 18% and p_t=2.5, continued.

Truck number	Axle Type	Axle load on uphill pavement (kN)	Equivalency Factor on uphill slope (E_i)	total weight of full-trailer (kN)	Te
9	S.A.S	24.38539	0.0089	530.7595	132.3394
	S.A	256.5255	114.7173		
	S.A	84.66433	1.2284		
	S.A	165.1843	16.3847		
10	S.A.S	31.53382	0.0252	568.5745	166.5691
	S.A	268.4775	141.3285		
	S.A	88.32719	1.4354		
	S.A	180.236	23.7800		
11	S.A.S	30.70767	0.0226	603.3024	211.7436
	S.A	280.4937	172.8652		
	S.A	92.45522	1.6979		
	S.A	199.6458	37.1579		
12	S.A.S	22.69163	0.0067	725.4291	563.9396
	S.A	349.0908	477.5994		
	S.A	115.045	3.8368		
	S.A	238.6017	82.4967		
Average truck equivalence factor (Ta)					79.2295

S.A.S. = Single axle single tired, S.A. = Single axle dual tires.

5

CHAPTER FIVE

DESIGN CHARTS OF TRUCK EQUIVALENCY FACTORS FOR FULL-TRAILER TRUCKS ON UPHILL FLEXIBLE PAVEMENTS

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DESIGN CHARTS OF TRUCK EQUIVALENCY FACTORS FOR FULL-TRAILER TRUCKS ON UPHILL FLEXIBLE PAVEMENTS

5.1 General

To simplify the design process for pavement designers, the truck equivalency factors of full-trailer trucks with different degrees of loading on uphill flexible pavements are presented as a set of charts. For this purpose, a computer program called DTCFUF (Drawing Truck equivalency factor Charts for Full-trailer trucks on Uphill Flexible pavements) was written in MATLAB to draw the charts of truck equivalency factor for full-trailer trucks on uphill flexible pavements as shown in Appendix E.

5.2 Design Charts

For both loaded and empty trucks of all types of full-trailer trucks covered in this study, the truck equivalency factors were obtained using the output of (FEFUF) computer program taking into consideration the effect of various parameters on the truck equivalency factors. These factors include the total weight of full-trailer, H/B ratio (height of the center of gravity to the wheelbase of the truck), magnitude of the uphill slope, and the structural number (SN). Due to limitations on time and space, only one value of 2.5 for the terminal level of serviceability p_t will be adopted in these charts.

For developing the charts, five values for H/B ratio of 0.2, 0.4, 0.6, 0.8, and 1.0 with a terminal level of serviceability p_t=2.5 and three values of the structural number SN= 2, 4, and 6 will be adopted.

For the use of the charts in the case of a highway with different uphill slopes, it is suggested either to adopt the maximum uphill slope or a weighted average uphill slope for determining the load equivalency factors for pavement design.

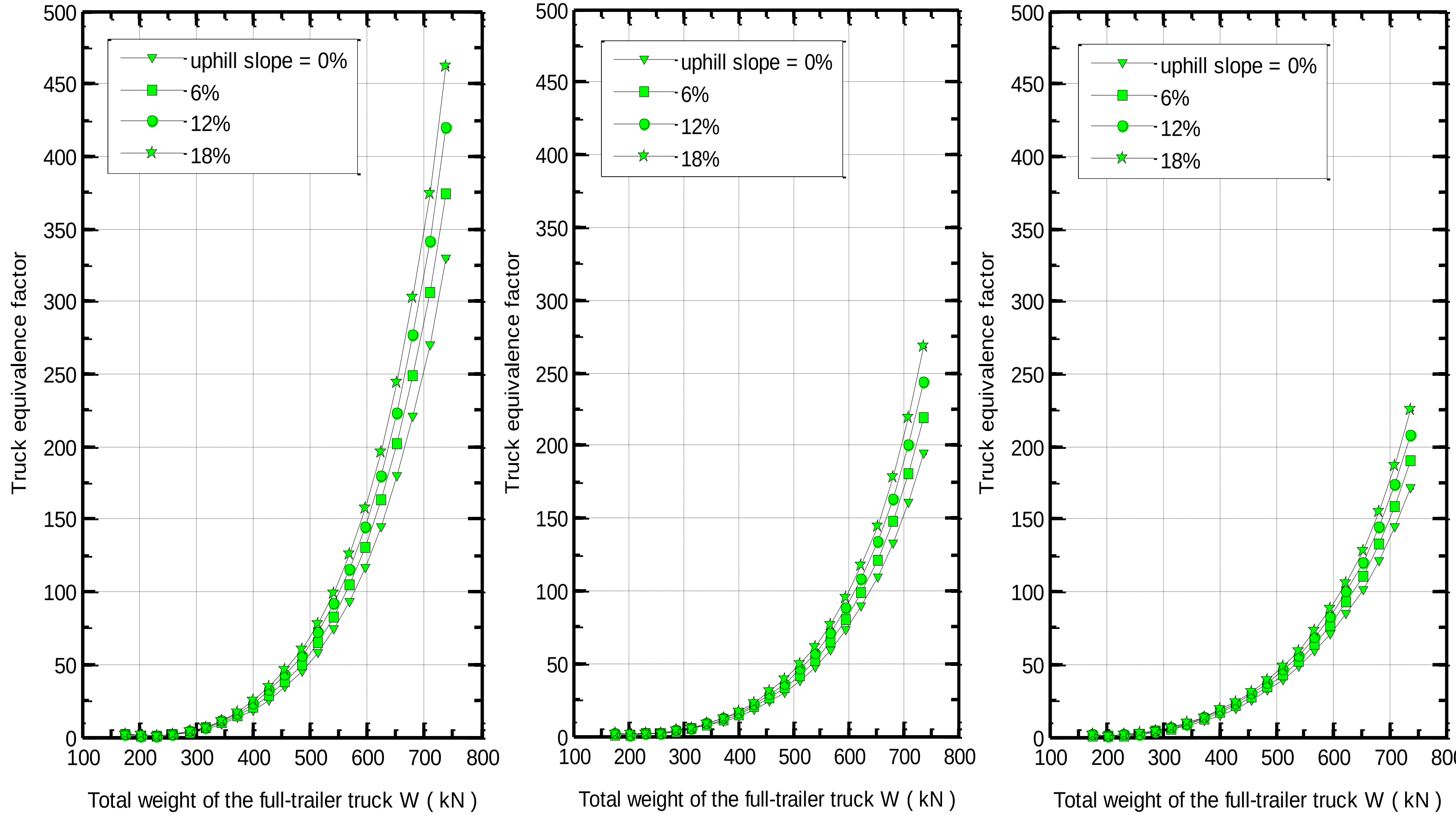
5.2.1 Design Charts for 1.2+2.2 Full-Trailer Trucks

For full-trailer truck type 1.2+2.2, Figures (5.1 to 5.5) show the truck equivalency factor versus full-trailer trucks weight for H/B of 0.2, 0.4, 0.6, 0.8 and 1.0, respectively.

Each figure consists of three charts. Each chart is devoted to a certain pavement structural number of 2, 4 or 6 for the same p_t and H/B ratio. Each chart shows the truck equivalency factor for four different uphill slope magnitudes of 0 (level road), 6, 12 and, 18%.

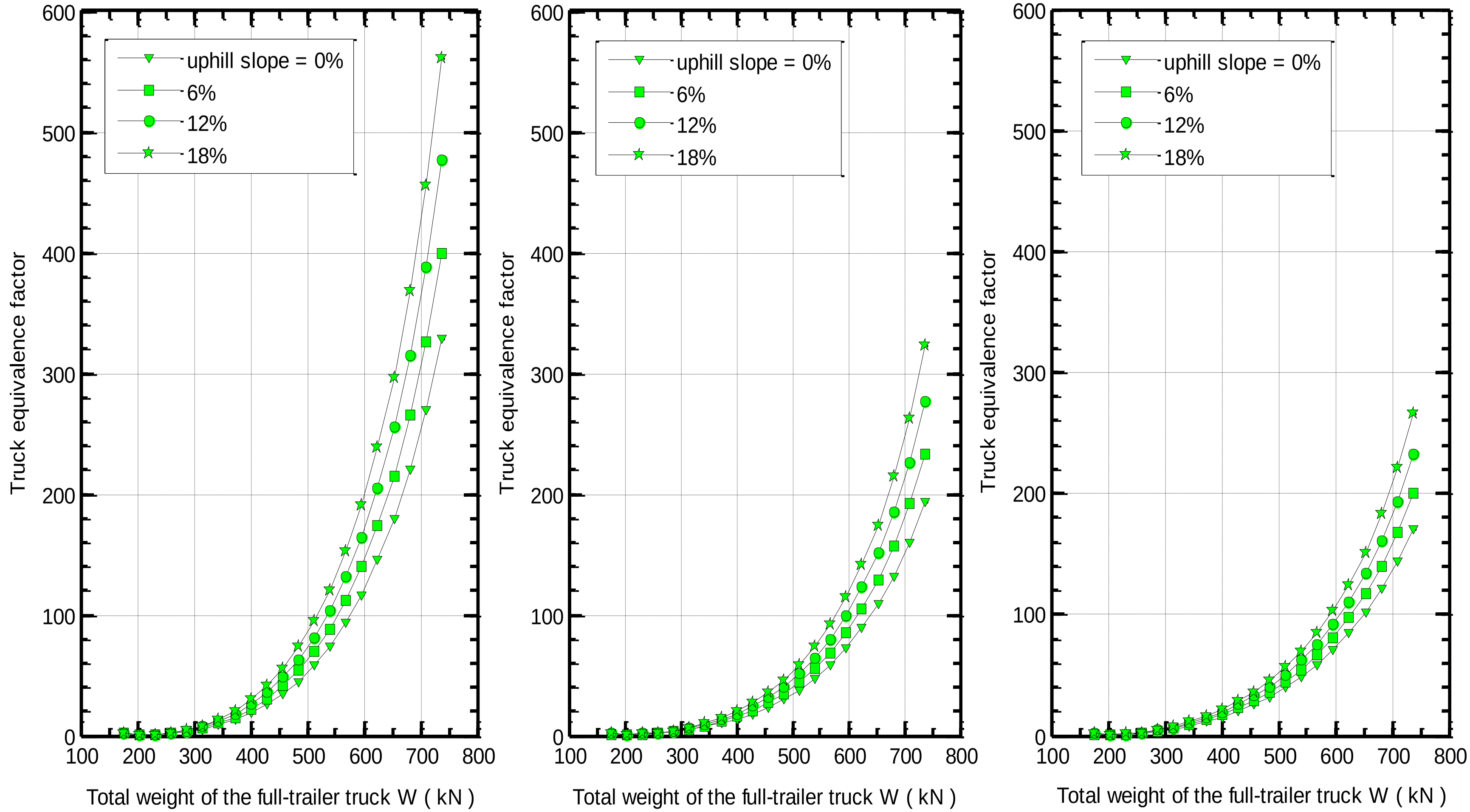
It is quite obvious from all charts that the truck equivalency factors increase non-linearly with increasing truck weight, for each H/B ratio and each magnitude of uphill slope.

It is also obvious that an increase in the magnitude of uphill slope causes an increase in the truck equivalency factor. This fact appears to be of significance for a total weight of full-trailer exceeding about 400 kN.



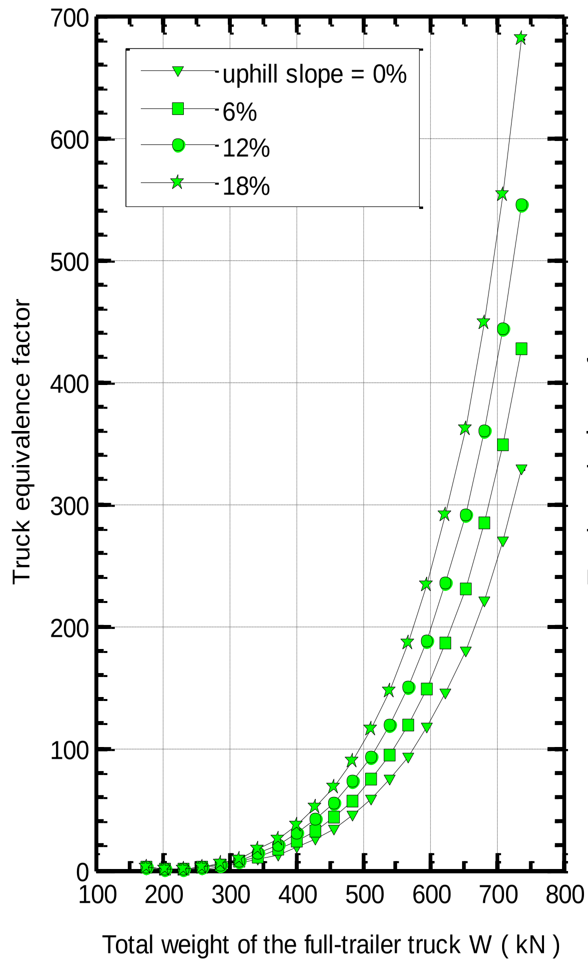
(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

Fig. (5.1) Truck equivalency factors for 1.2+2.2 full-trailers on uphill flexible pavements (case: H/B=0.2, p_t=2.5).

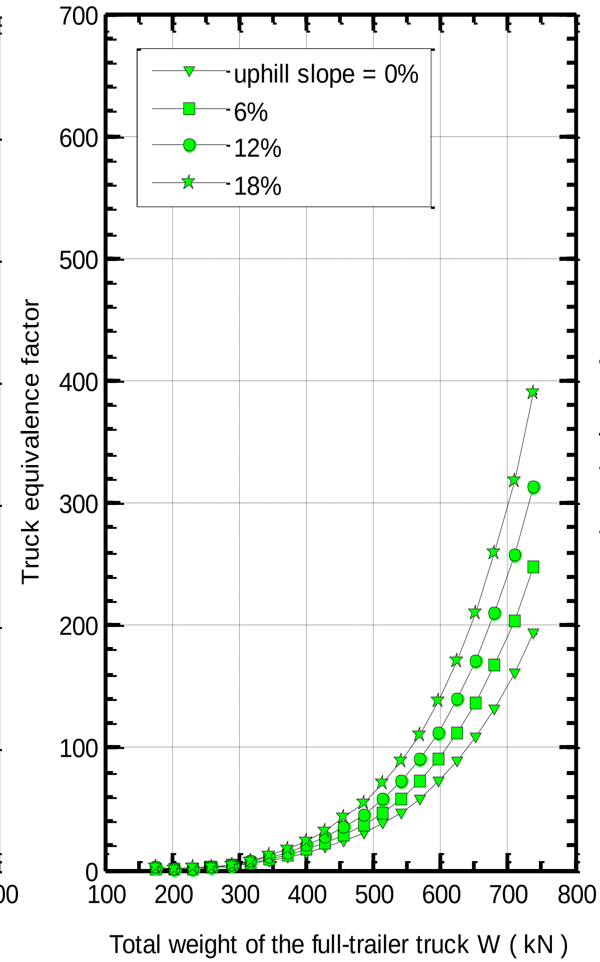


(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

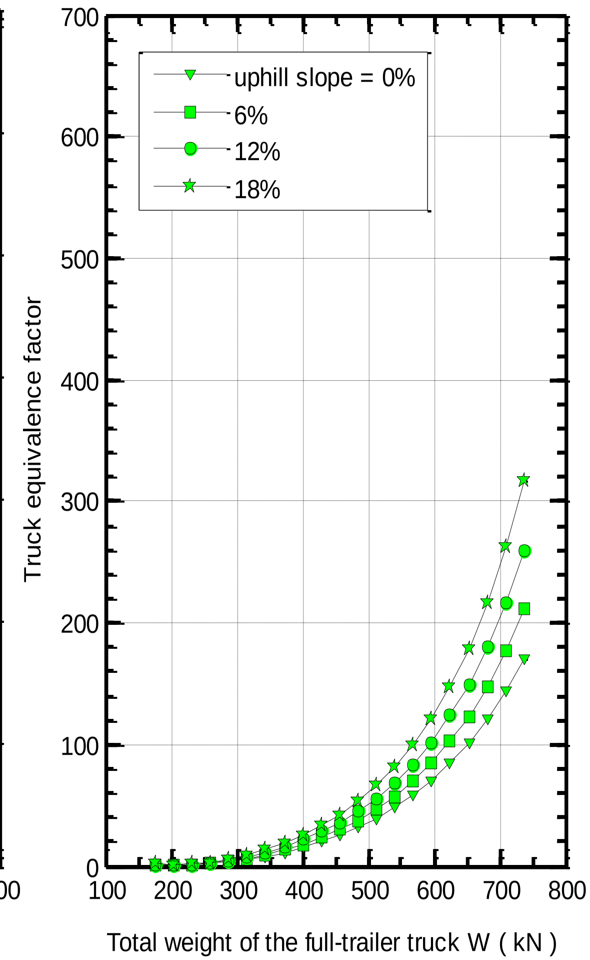
Fig. (5.2) Truck equivalency factors for 1.2+2.2 full-trailers on uphill flexible pavements (case: H/B=0.4, p_t=2.5).



(A) SN = 2

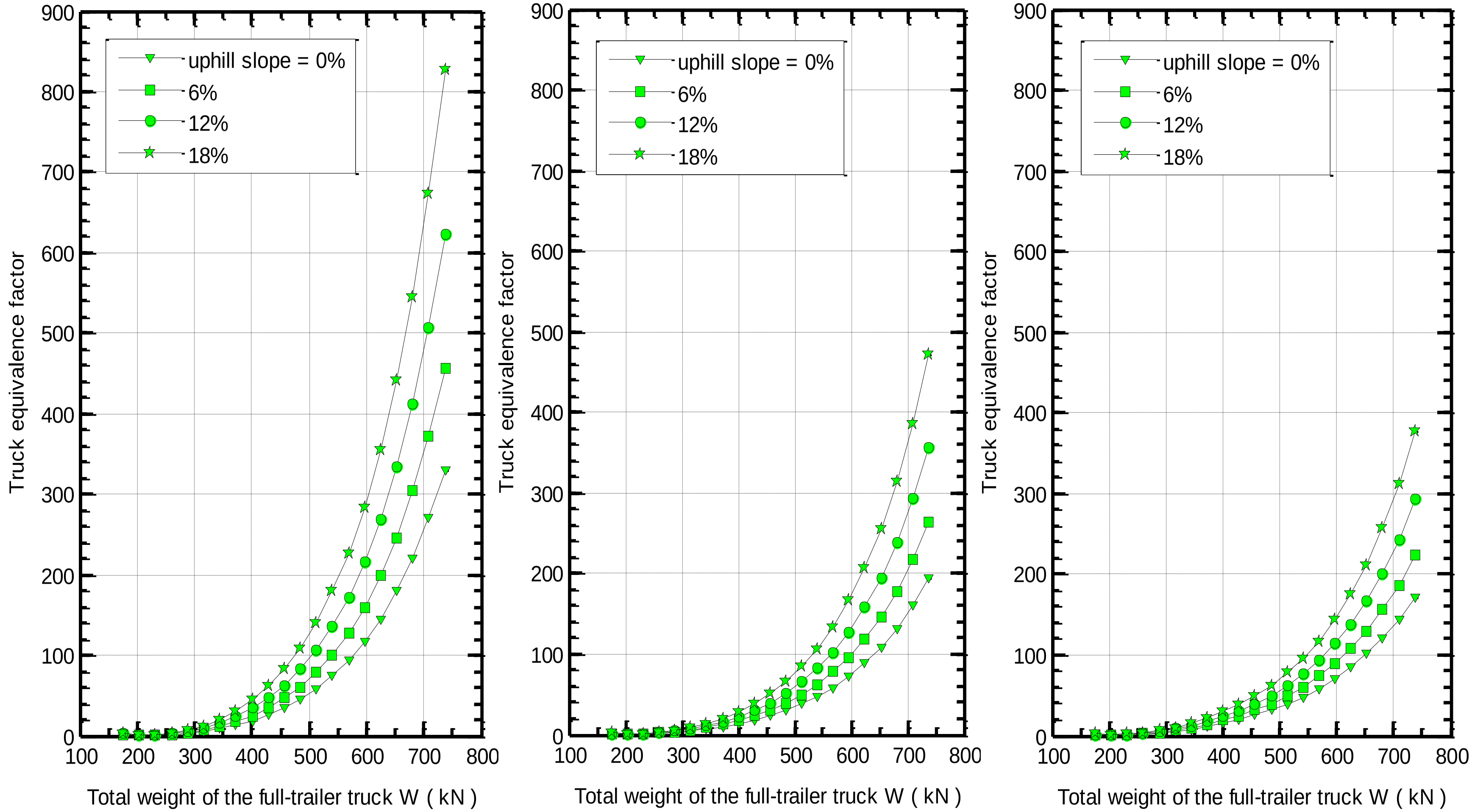


(B) SN = 4



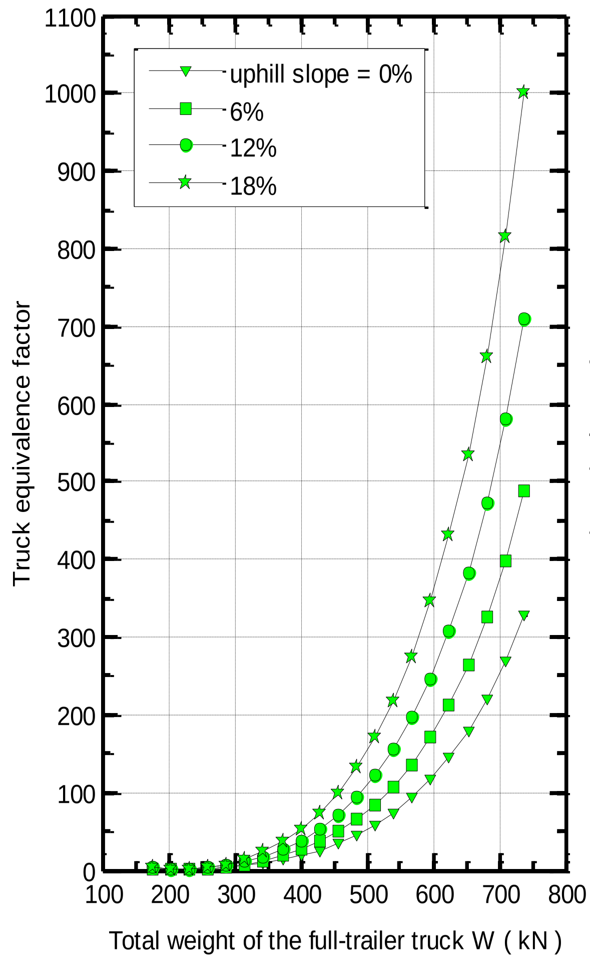
(C) SN = 6

Fig. (5.3) Truck equivalency factors for 1.2+2.2 full-trailers on uphill flexible pavements (case: H/B=0.6, p_t=2.5).

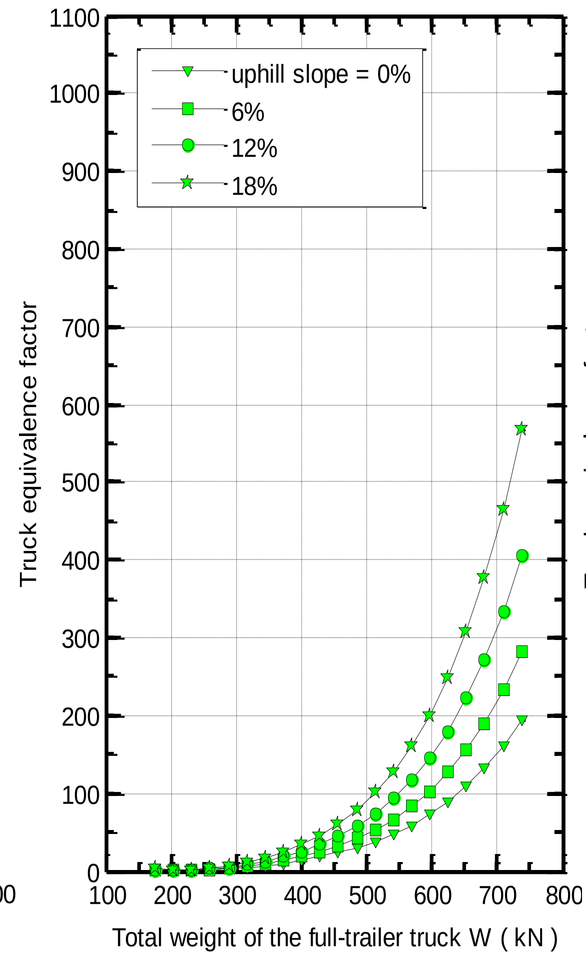


(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

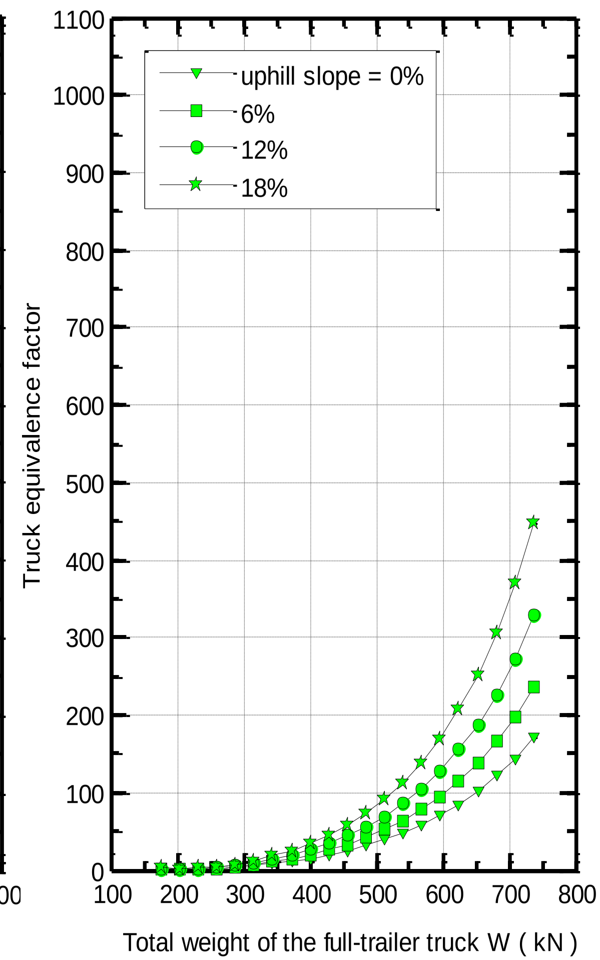
Fig. (5.4) Truck equivalency factors for 1.2+2.2 full-trailers on uphill flexible pavements (case: H/B=0.8, p_t=2.5).



(A) SN = 2



(B) SN = 4



(C) SN = 6

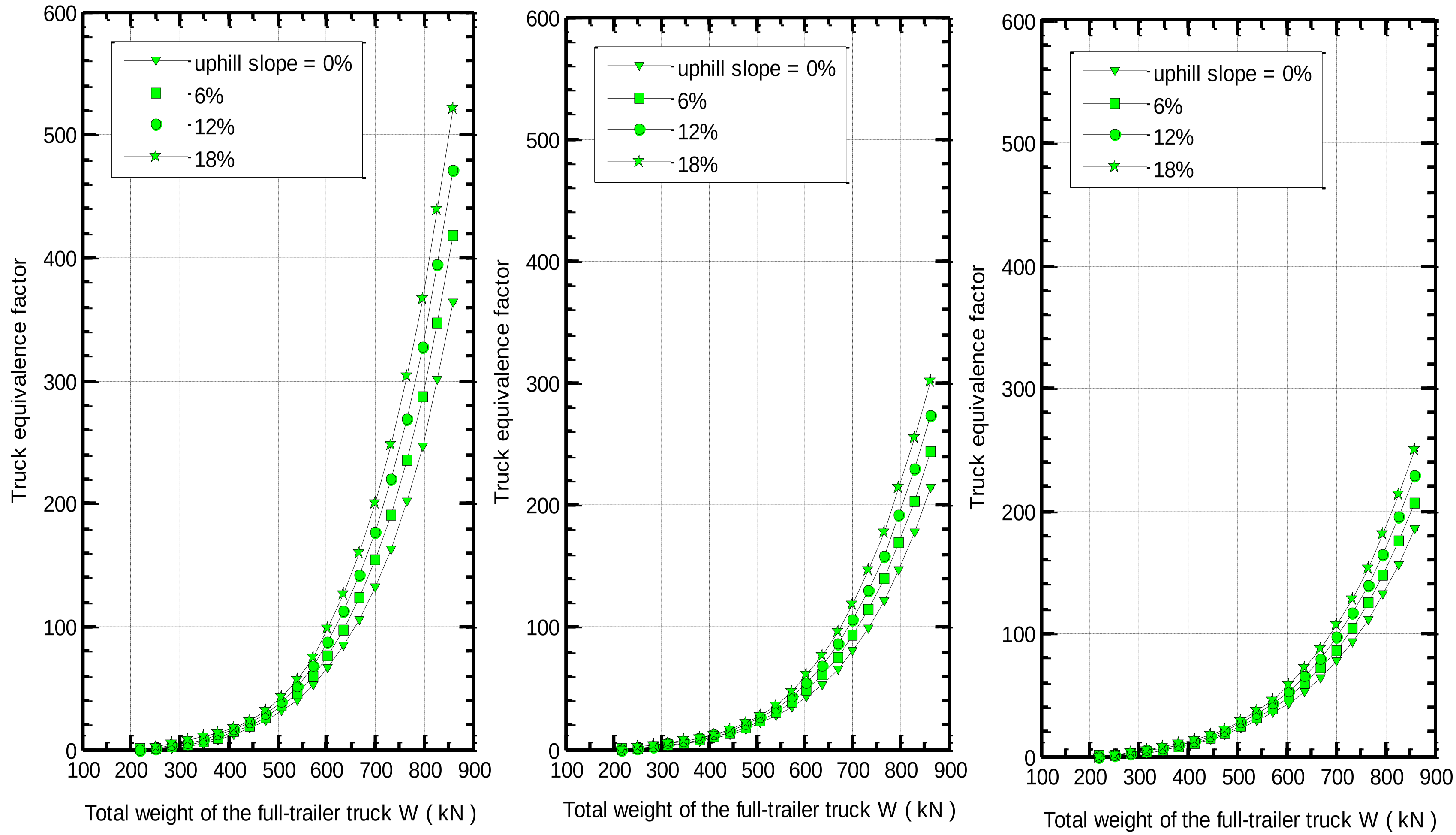
Fig. (5.5) Truck equivalency factors for 1.2+2.2 full-trailers on uphill flexible pavements (case: H/B=1, p_t=2.5).

5.2.2 <u>Design Charts for 1.2+2.22 Full-Trailer</u>

Figures (5.6 to 5.10) show the truck equivalency factor for full-trailer truck type 1.2+2.22 for the same values of SN, H/B ratio and terminal level of serviceability adopted for full-trailer type1.2+2.2.

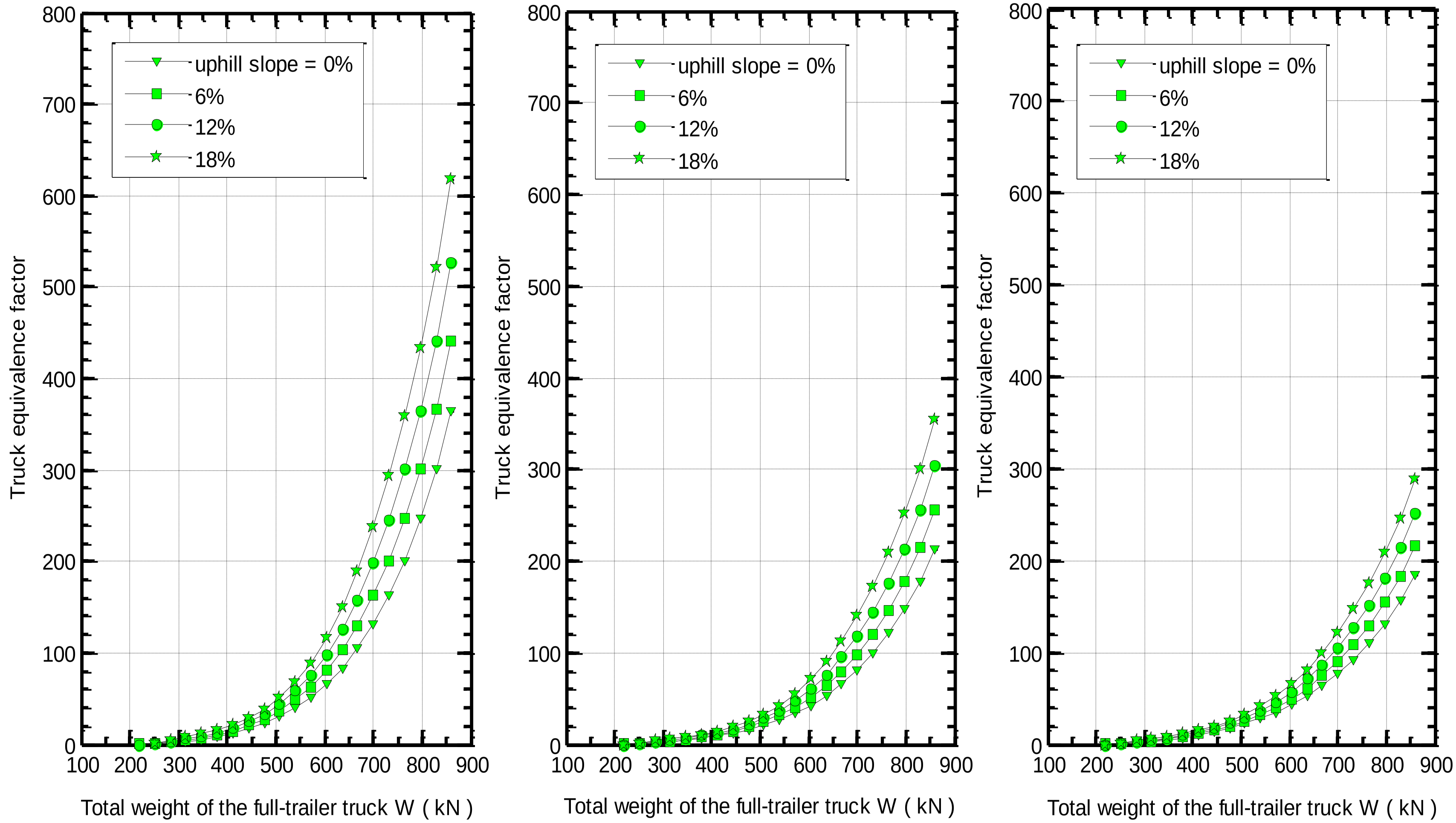
A thorough study of all design charts for 1.2+2.22 full-trailer trucks reveals that the effect of uphill slope on the truck equivalency factors becomes pronounced for truck weight exceeding about 400 kN indicating that this effect is of great importance for developing countries in which the phenomenon of overloading is very common.

As in the case of 1.2+2.2 full-trailer trucks, an increase in the uphill slope causes a significant increase in the truck equivalency factor, while an increase in the structural number SN causes a decrease in this truck equivalency number as it will be discussed in depth later in section (5.3).



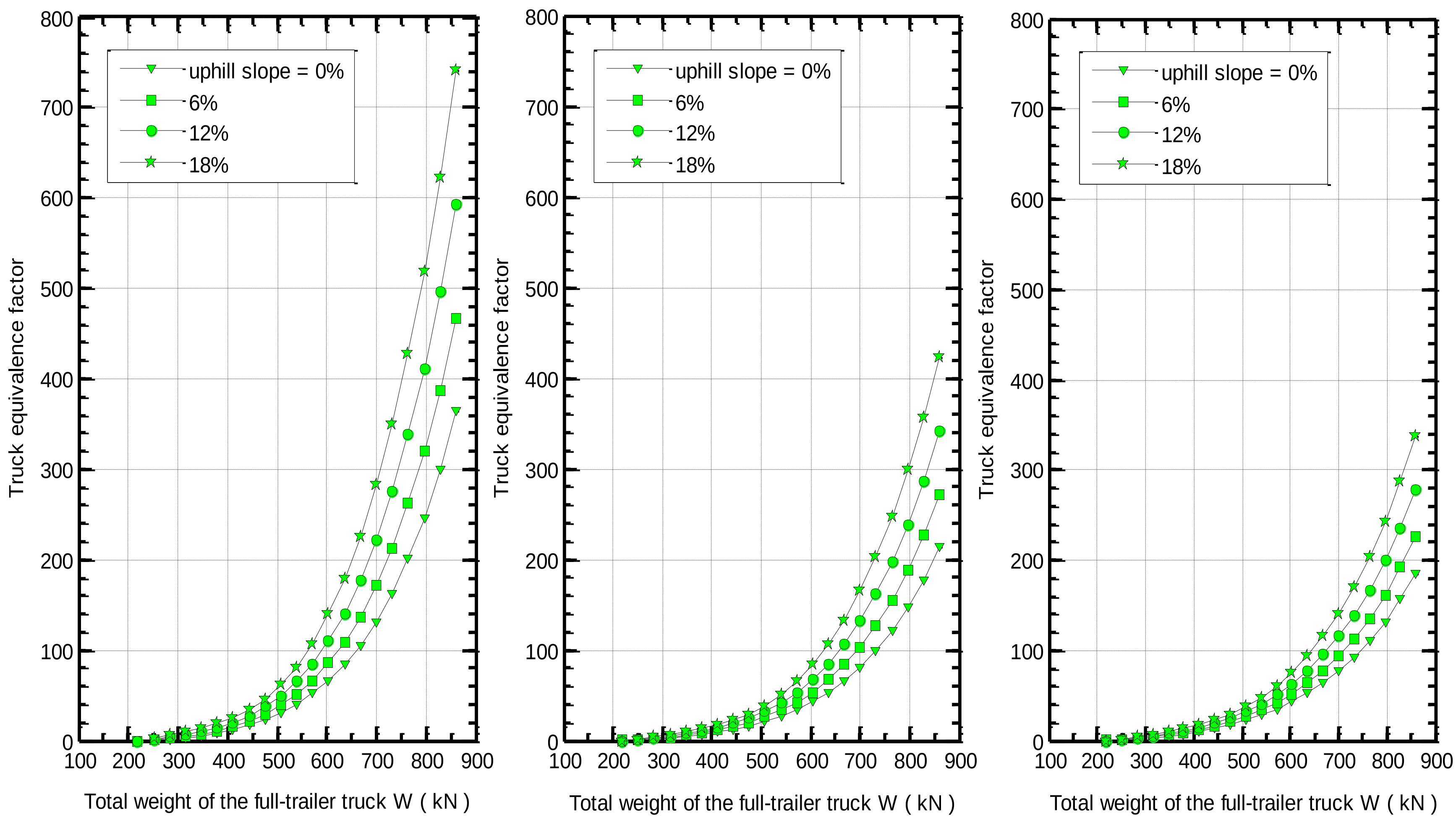
(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

Fig. (5.6) Truck equivalency factors for 1.2+2.22 full-trailers on uphill flexible pavements (case: H/B=0.2, p_t=2.5).



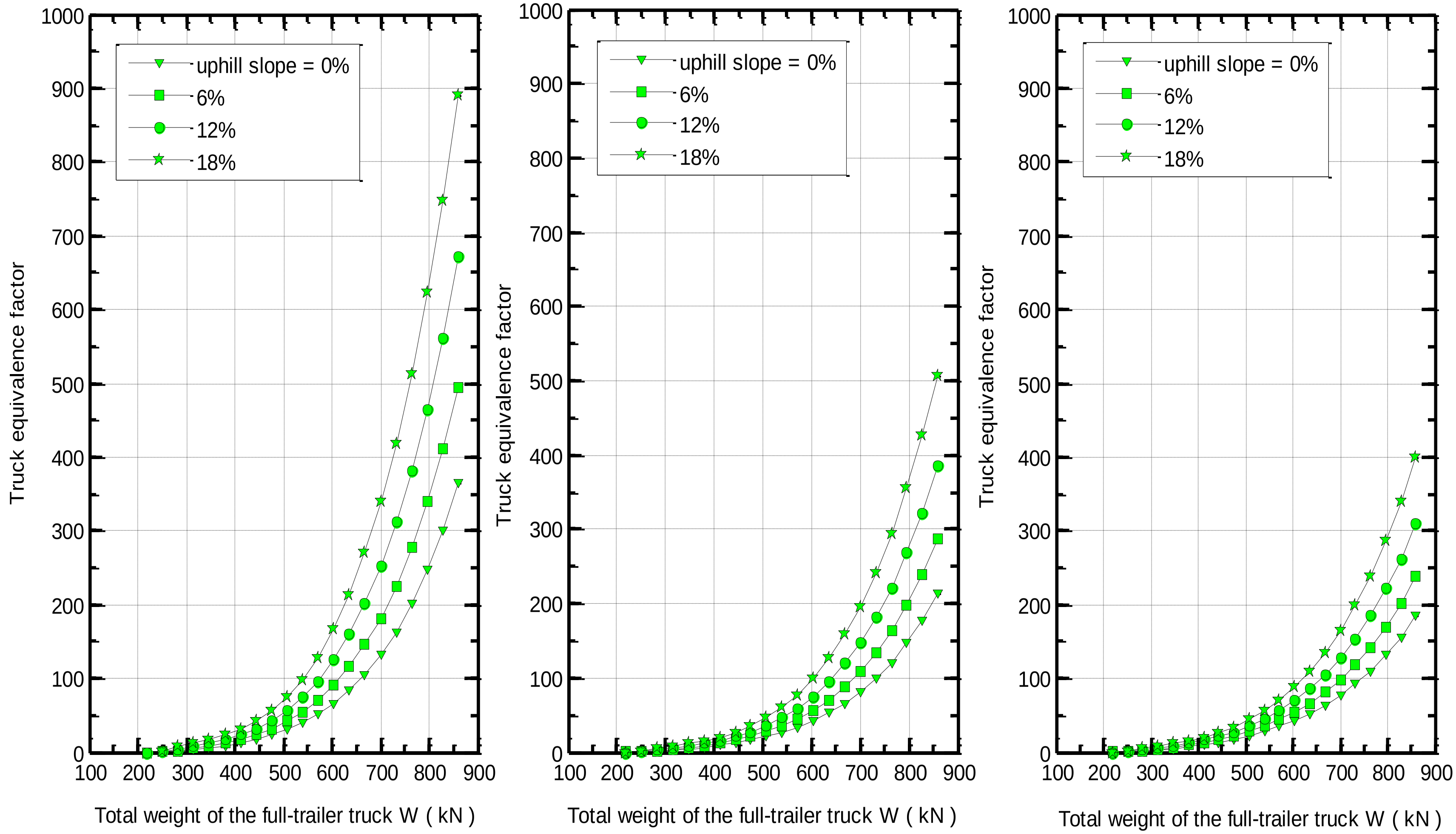
(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

Fig. (5.7) Truck equivalency factors for 1.2+2.22 full-trailers on uphill flexible pavements (case: H/B=0.4, p_t=2.5).



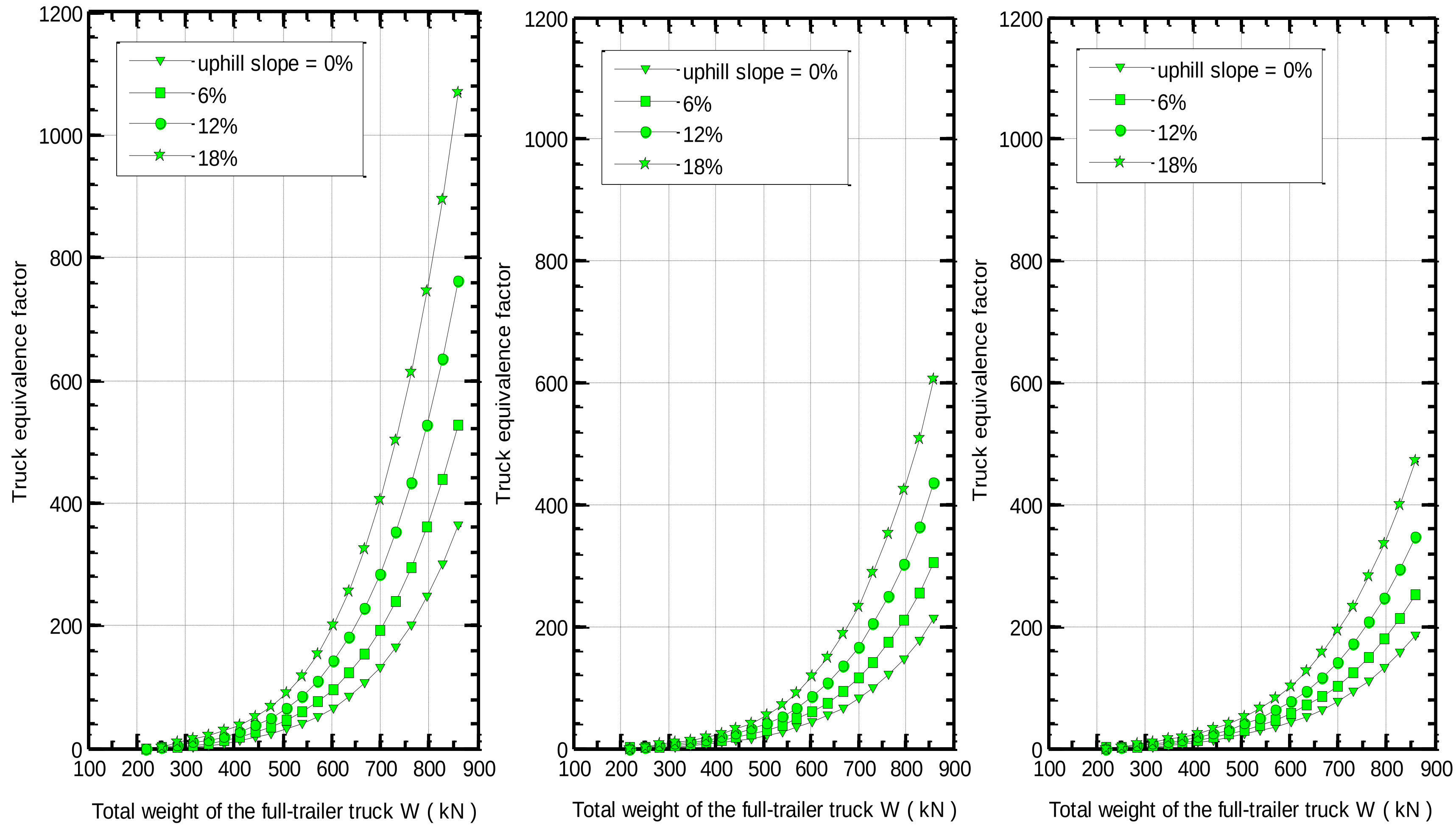
(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

Fig. (5.8) Truck equivalency factors for 1.2+2.22 full-trailers on uphill flexible pavements (case: H/B=0.6, p_t=2.5).



(A) SN = 2 (B) SN = 4 (C) SN = 6

Fig. (5.9) Truck equivalency factors for 1.2+2.22 full-trailers on uphill flexible pavements (case: H/B=0.8, p_t=2.5).



(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

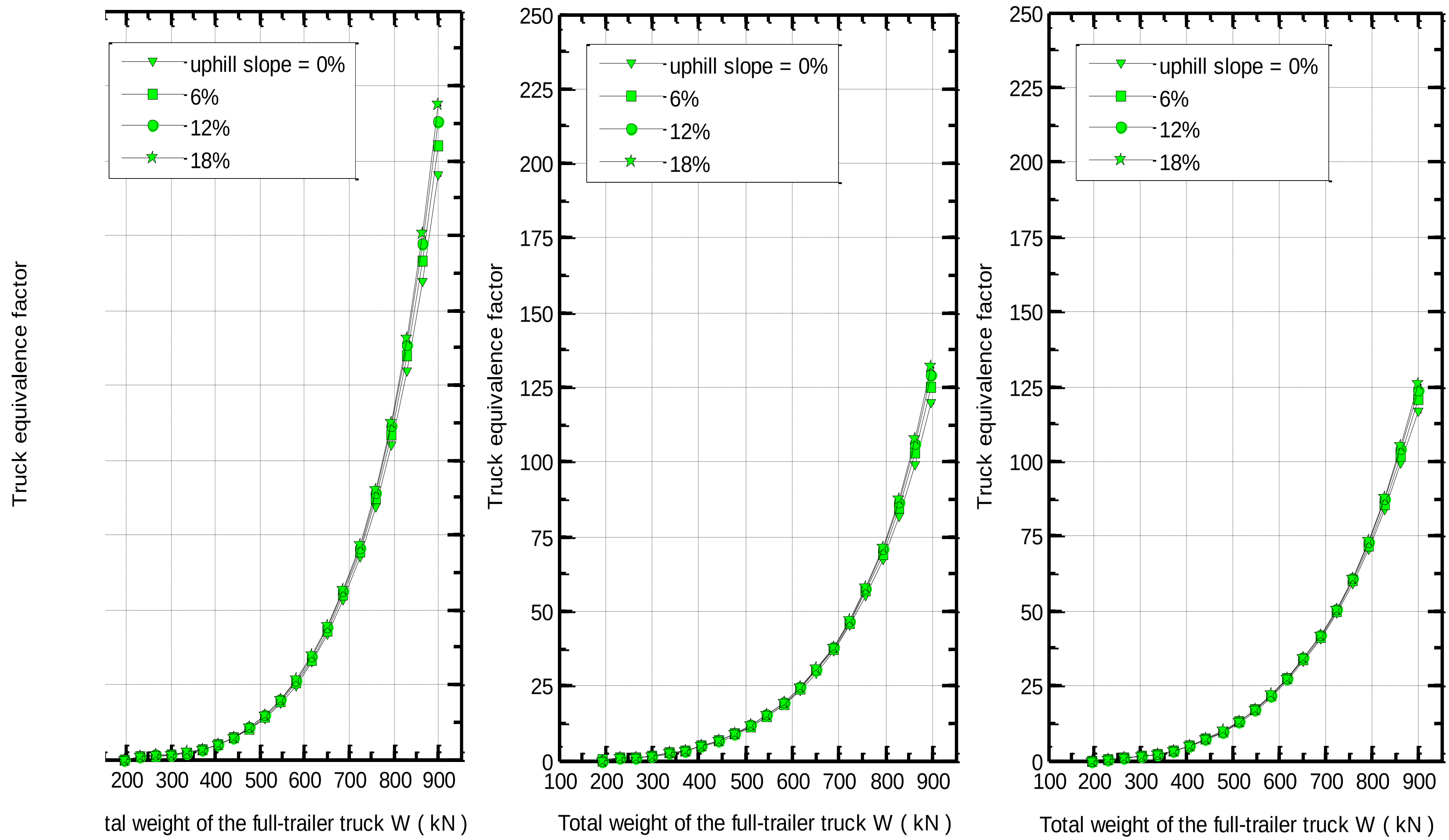
Fig. (5.10) Truck equivalency factors for 1.2+2.22 full-trailers on uphill flexible pavements (case: H/B=1, p_t=2.5).

5.2.3 Design Charts for 1.22+2.2 Full-Trailer

For full-trailer truck type 1.22+2.2, Figures (5.11 to 5.15) show the truck equivalency factors versus the total weight of full-trailer for the same values of full-trailer weight, H/B ratio, uphill slope and structural number adopted for 1.2+2.2 full-trailer type.

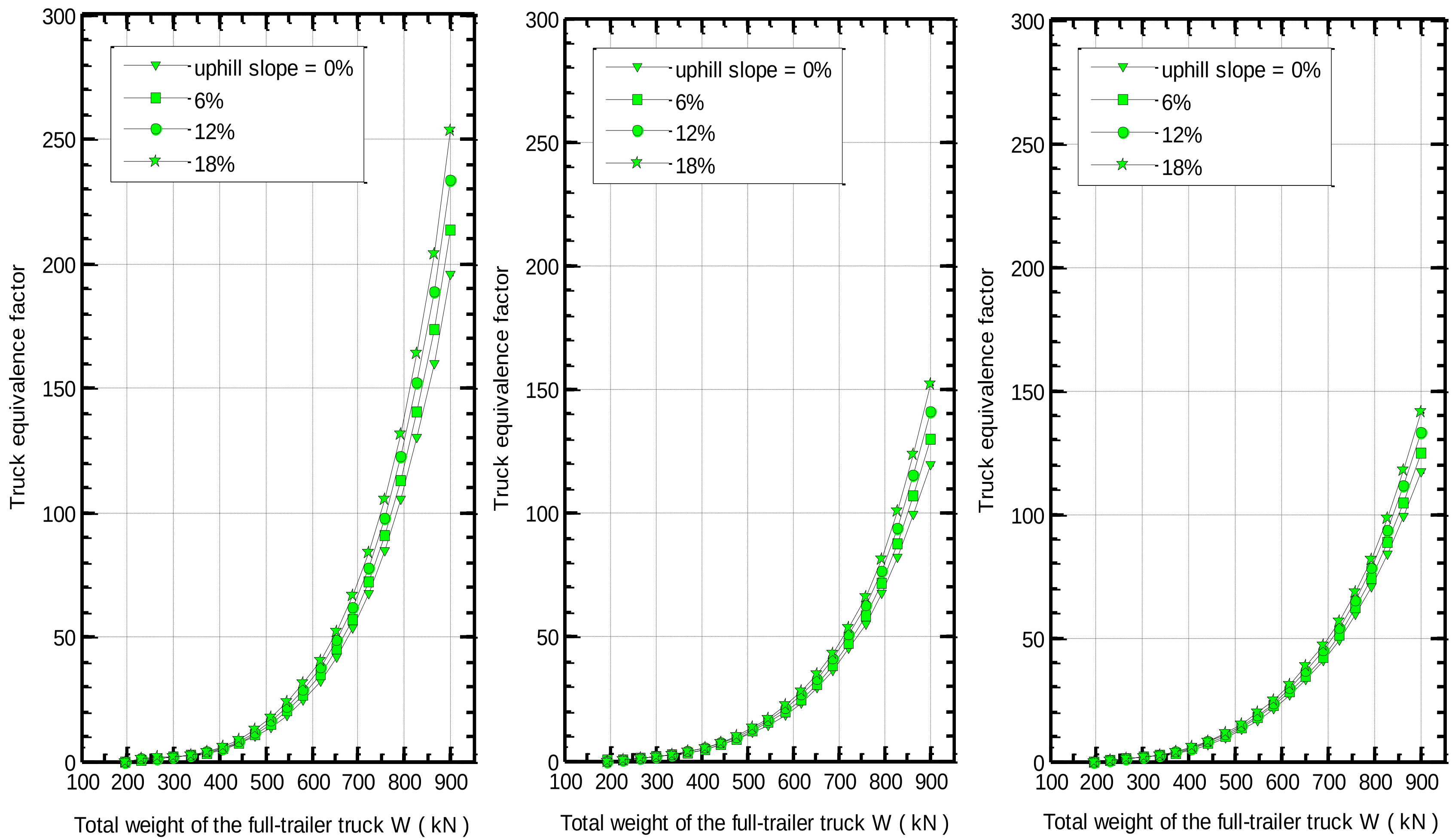
It is quite obvious from all charts that the truck equivalency factors increase non-linearly with increasing truck weight similar to the previous cases for each H/B ratio and upgrade magnitude. However, for small values of H/B $\leq$ 0.4, the curves in each chart appear to be close to each other indicating that the effect of an upgrade in such cases is insignificant.

However, For H/B $\geq$ 0.6 the effect of upgrade magnitude on the truck equivalency factor appears to be of significance for a total weight of full-trailer exceeding about 500 kN. At about 500 kN the curves in each chart start to diverge from each other indicating the importance of upgrade magnitude.



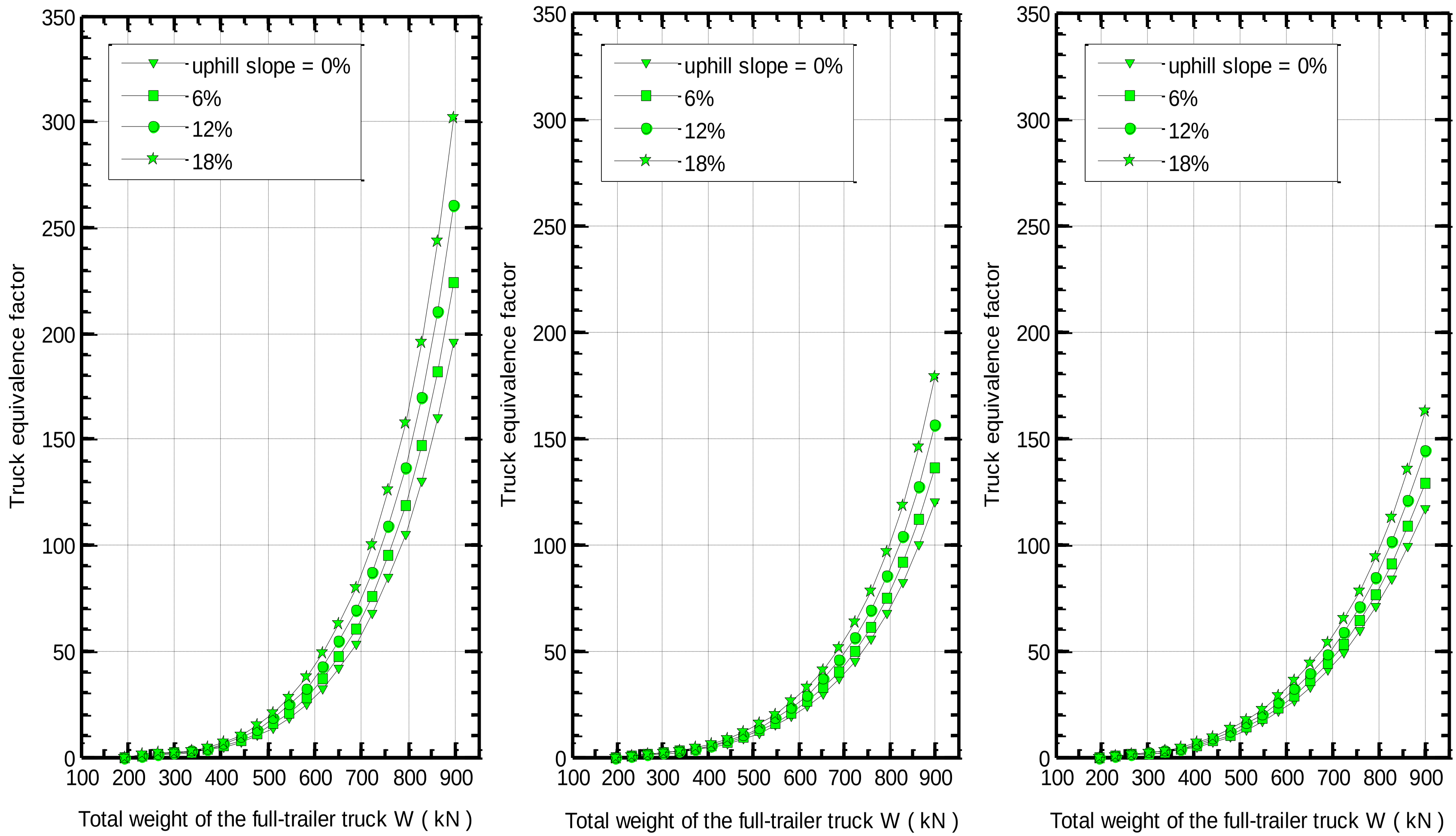
(A) SN = 2 (B) SN = 4 (C) SN = 6

Fig. (5.11) Truck equivalency factors for 1.22+2.2 full-trailers on uphill flexible pavements (case: H/B=0.2, p_t=2.5).



(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

Fig. (5.12) Truck equivalency factors for 1.22+2.2 full-trailers on uphill flexible pavements (case: H/B=0.4, p_t=2.5).



(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

Fig. (5.13) Truck equivalency factors for 1.22+2.2 full-trailers on uphill flexible pavements (case: H/B=0.6, p_t=2.5).

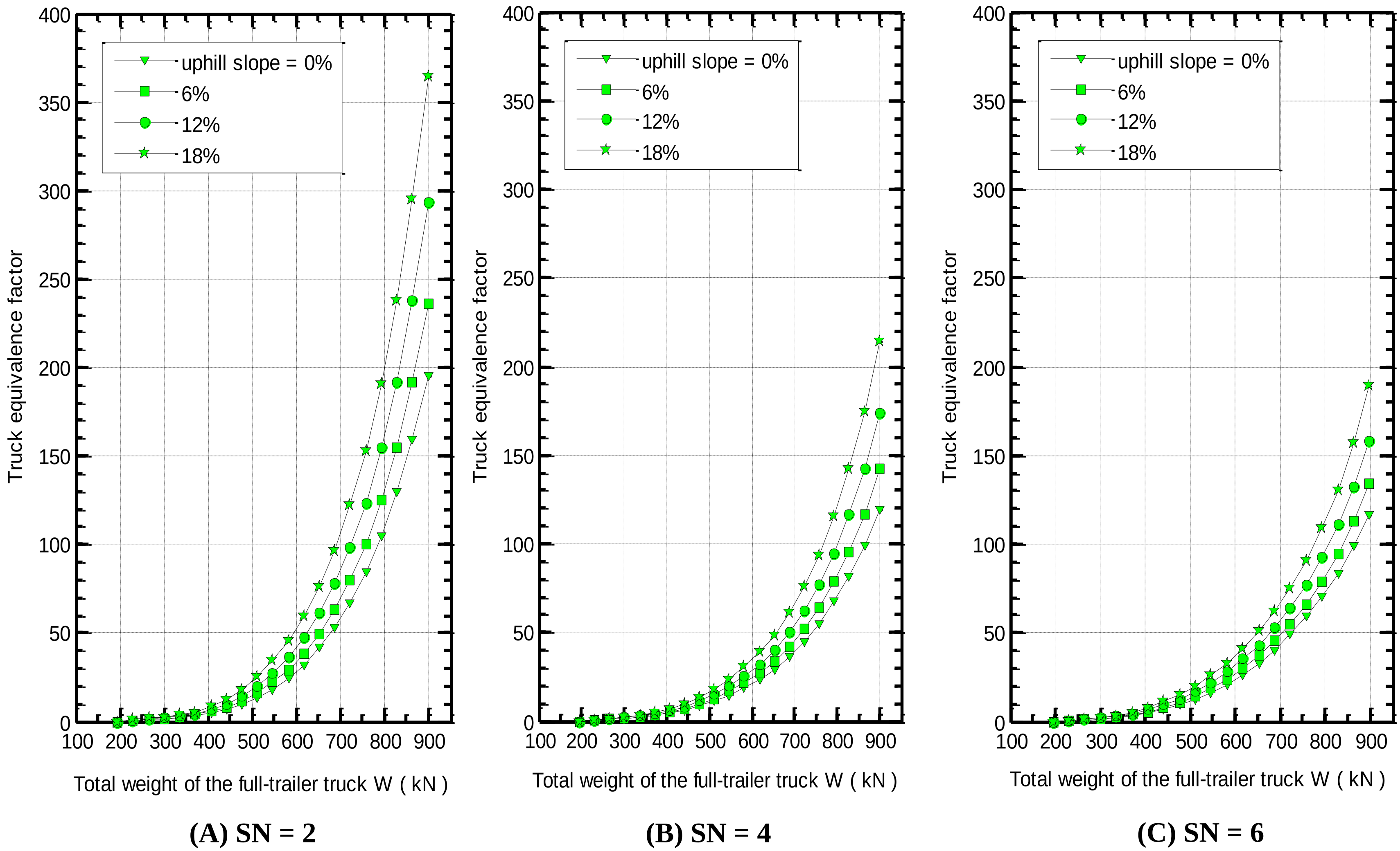
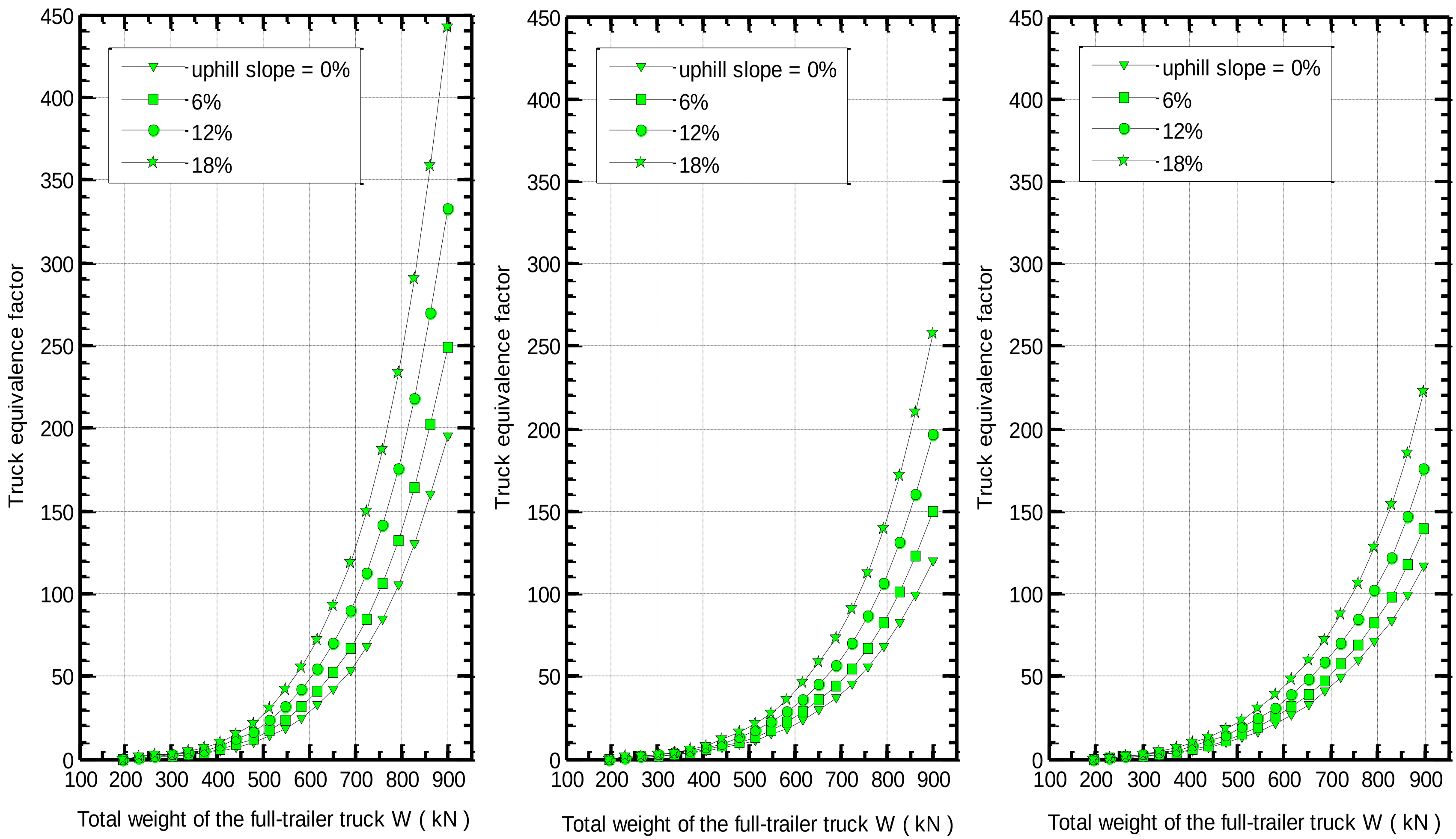


Fig. (5.14) Truck equivalency factors for 1.22+2.2 full-trailers on uphill flexible pavements (case: H/B=0.8, p_t=2.5).



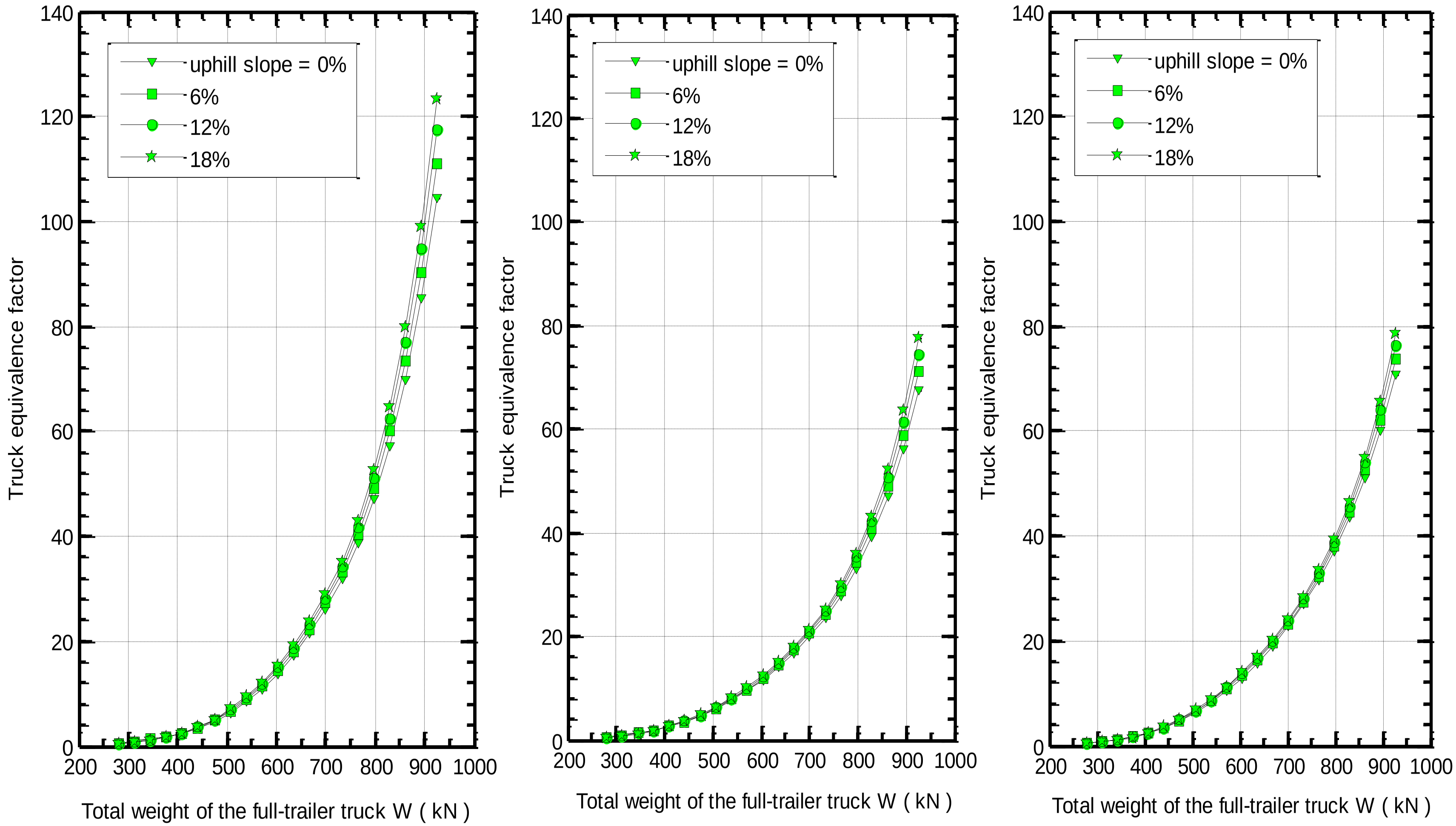
(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

Fig. (5.15) Truck equivalency factors for 1.22+2.2 full-trailers on uphill flexible pavements (case: H/B=1, p_t=2.5).

5.2.4 Design Charts of 1.22+2.22 Full-Trailer

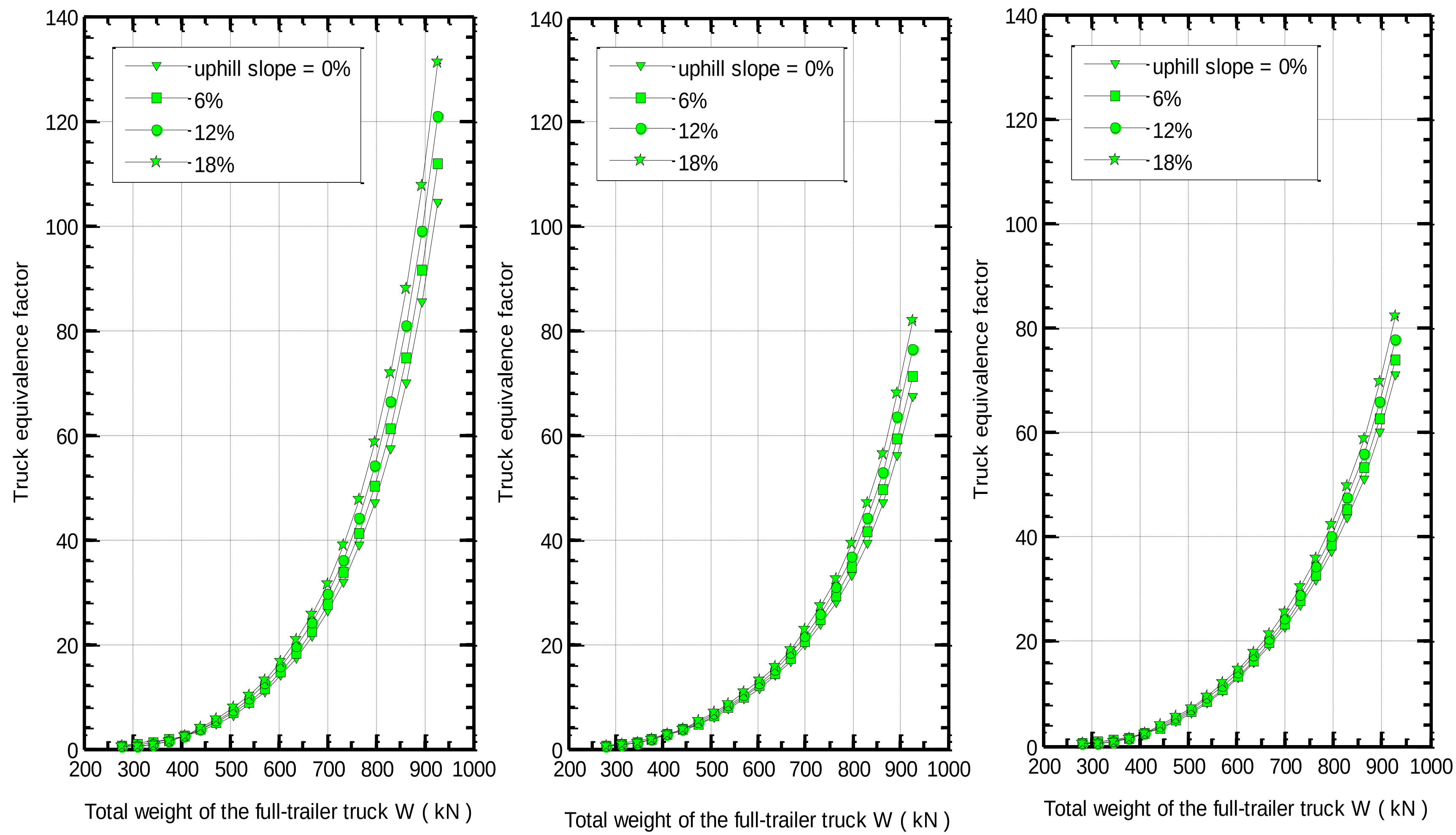
Figures (5.16 to 5.20) show the truck equivalency factors for full-trailer truck type 1.22+2.22 for the same values of SN, H/B ratio and terminal level of serviceability adopted for full-trailer type1.2+2.2.

It is quite obvious when comparing these figures with those of 1.2+2.2 full-trailer that the truck equivalency factor for 1.22+2.22 full-trailer is much less than that obtained for 1.2+2.2 full-trailer type having the same weight due to the existence of tandem axles, which are much less damaging than single axles carrying the same load. The truck equivalency factor increases with increasing magnitude of an upgrade for the same values of H/B ratio and SN.



(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

Fig. (5.16) Truck equivalency factors for 1.22+2.22 full-trailers on uphill flexible pavements (case: H/B=0.2, p_t=2.5).

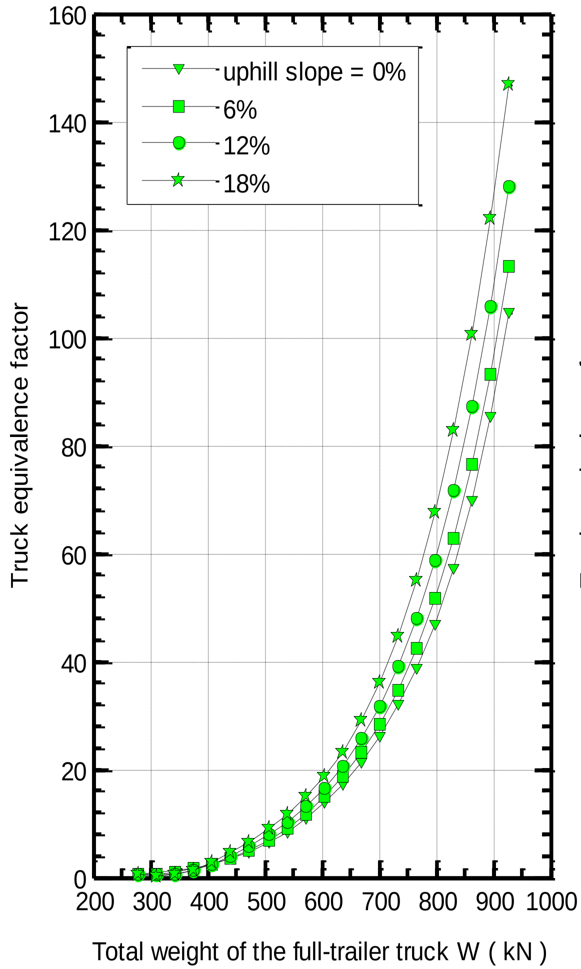


(A) SN = 2

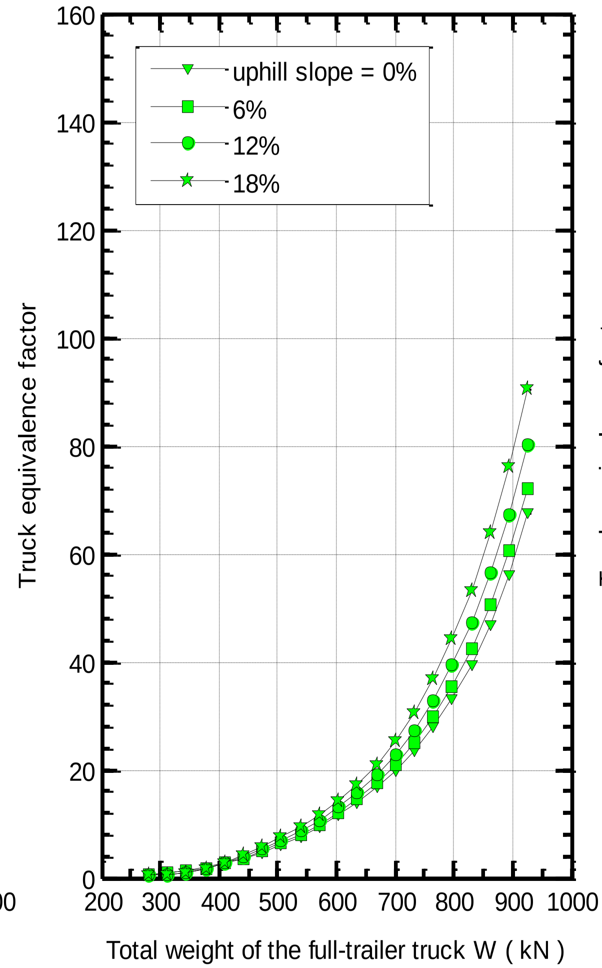
(B) SN = 4

(C) SN = 6

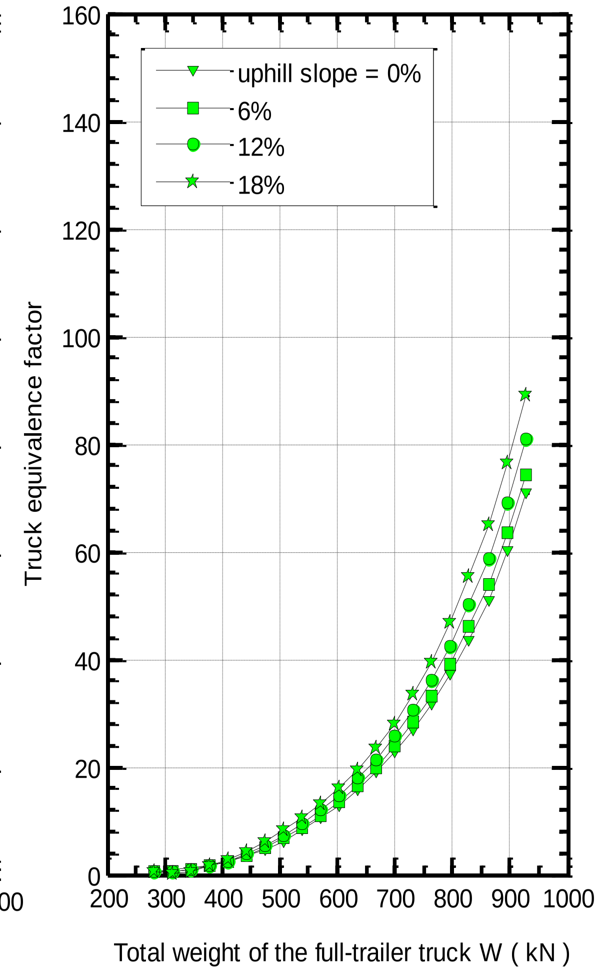
Fig. (5.17) Truck equivalency factors for 1.22+2.22 full-trailers on uphill flexible pavements (case: H/B=0.4, p_t=2.5).



(A) SN = 2

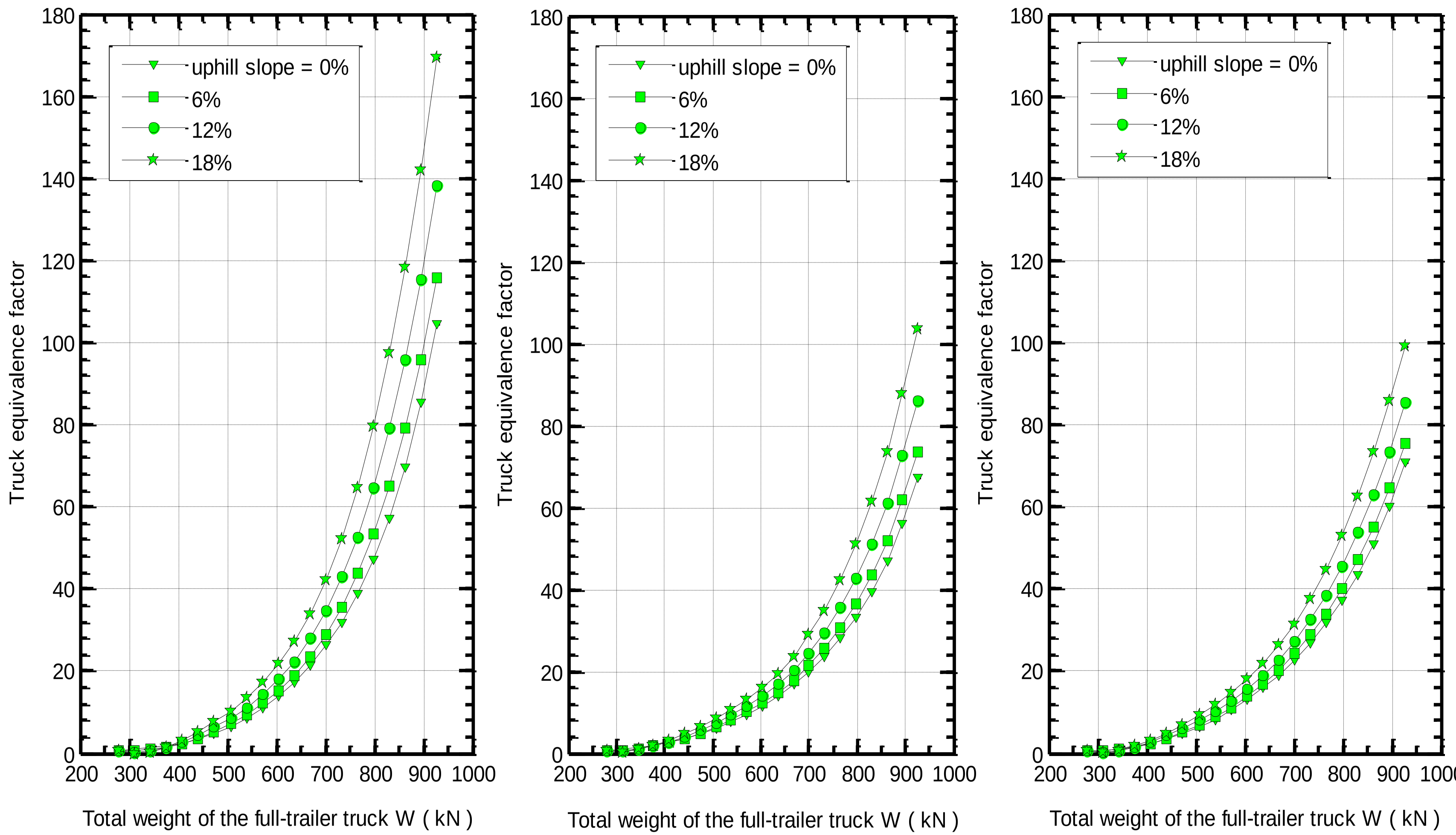


(B) SN = 4



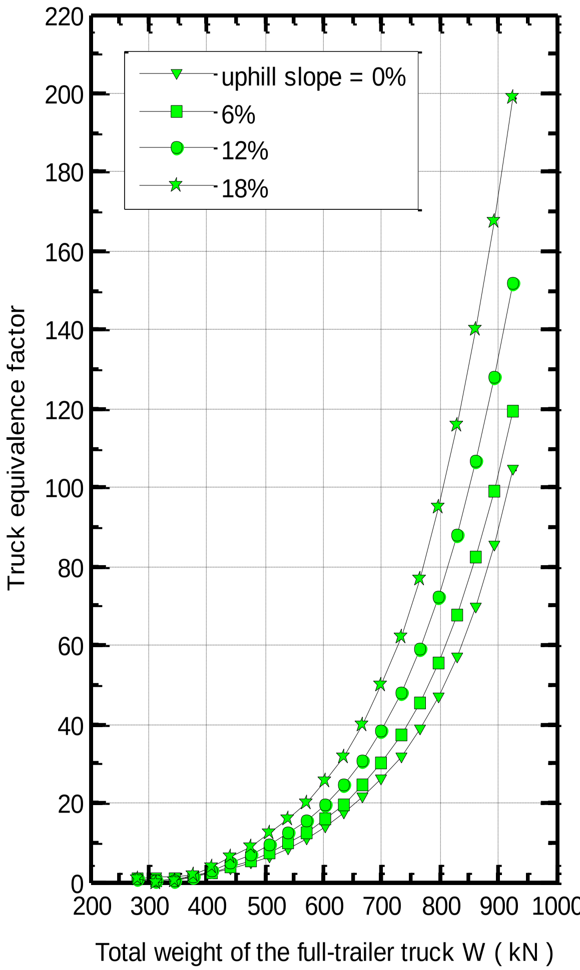
(C) SN = 6

Fig. (5.18) Truck equivalency factors for 1.22+2.22 full-trailers on uphill flexible pavements (case: H/B=0.6, p_t=2.5).

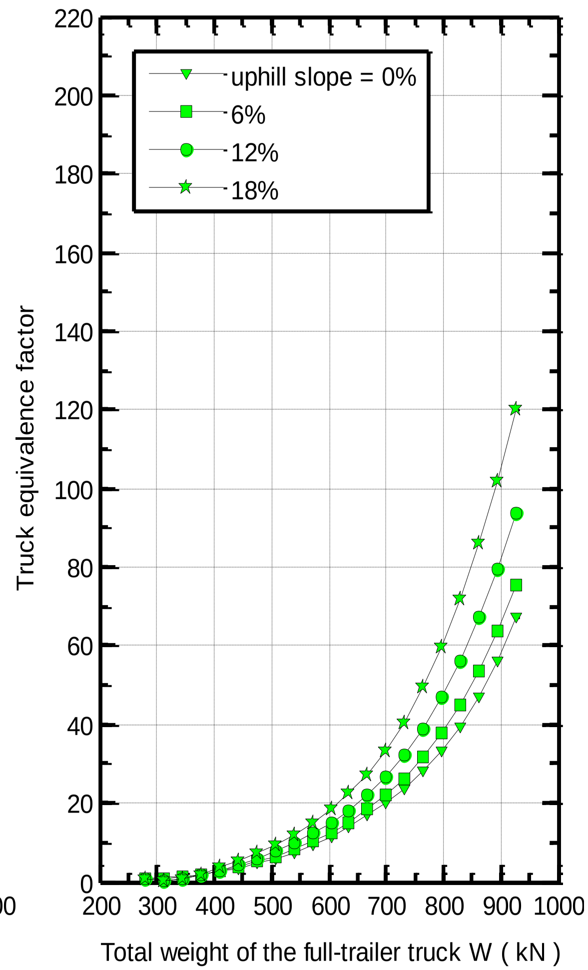


(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

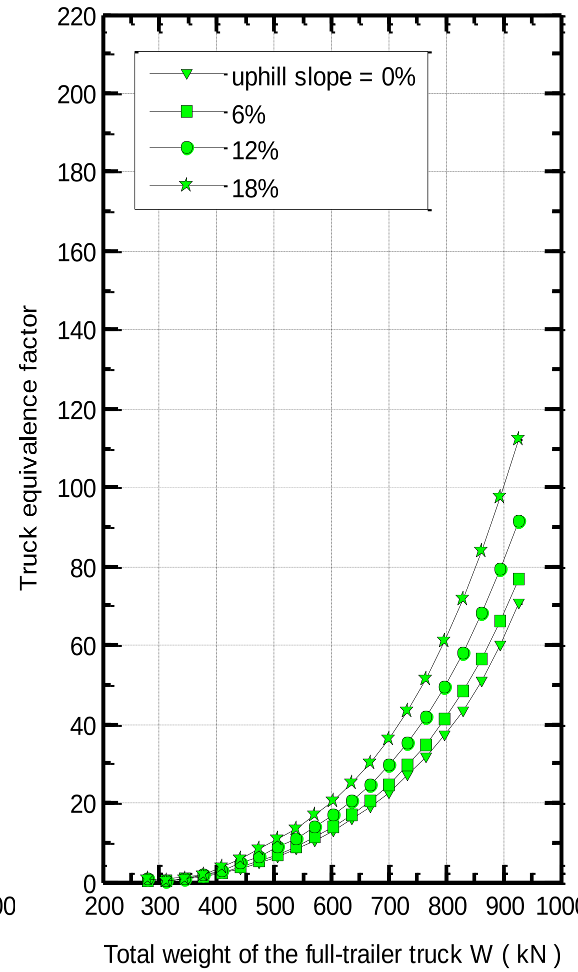
Fig. (5.19) Truck equivalency factors for 1.22+2.22 full-trailers on uphill flexible pavements (case: H/B=0.8, p_t=2.5).



(A) SN = 2



(B) SN = 4



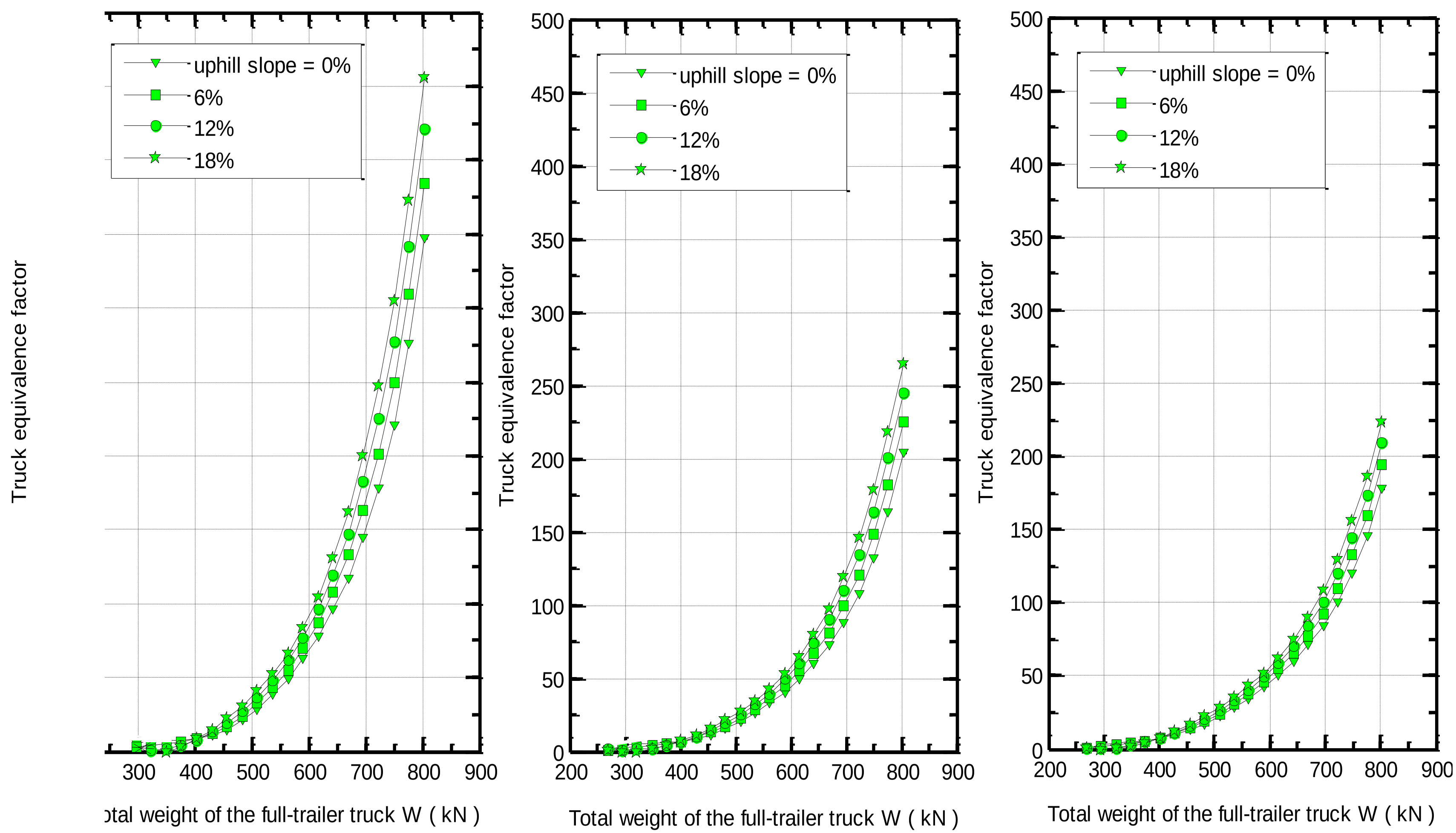
(C) SN = 6

Fig. (5.20) Truck equivalency factors for 1.22+2.22 full-trailers on uphill flexible pavements (case: H/B=1, p_t=2.5).

5.2.5 <u>Design Charts for 11.2+2.2 Full-Trailer</u>

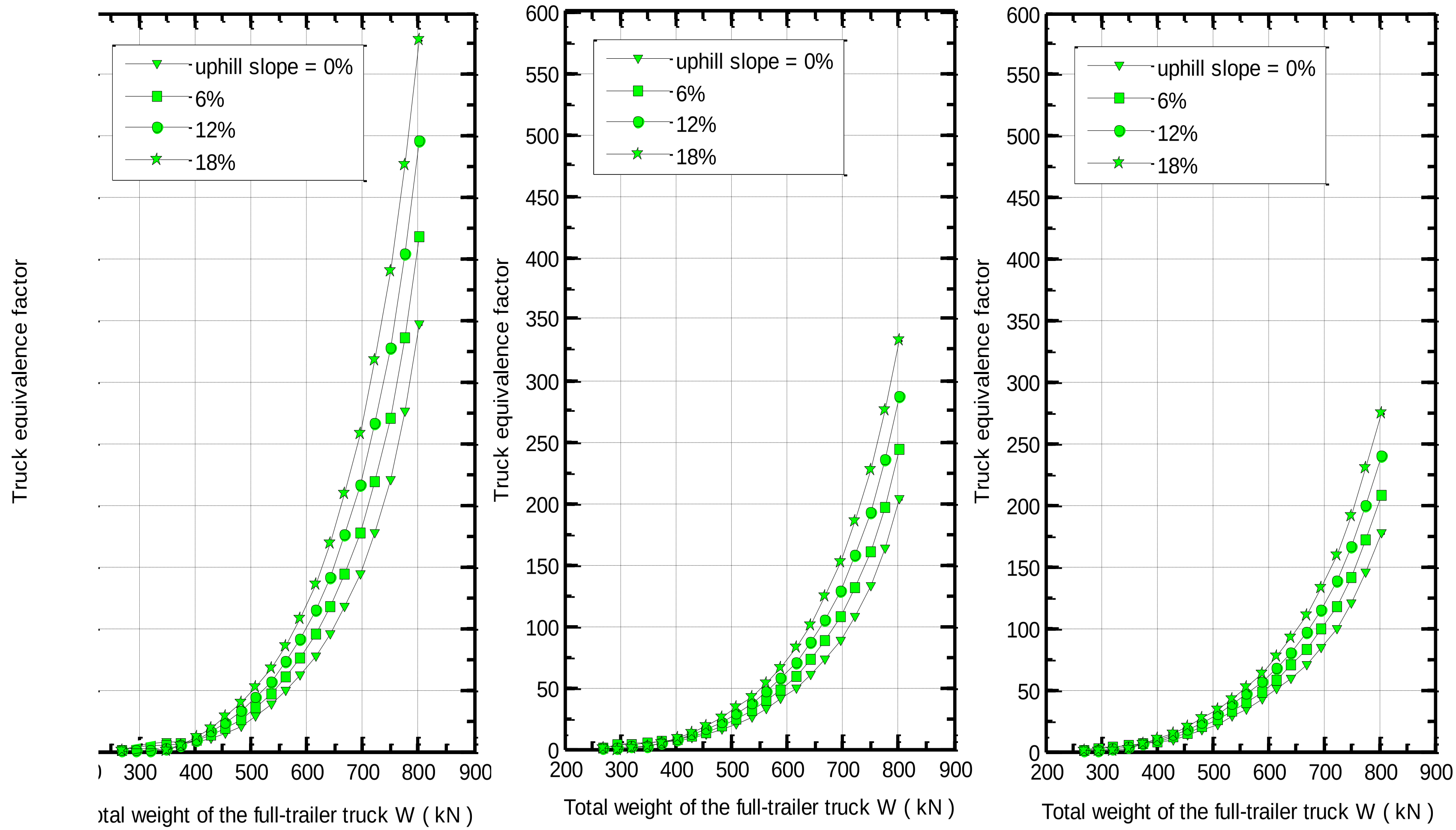
Figures (5. 21to 5.25) show the truck equivalency factors for full-trailer truck type 11.2+2.2 for the same values of SN, H/B ratio, and upgrade magnitude adopted for 1.2+2.2 full-trailer type.

Similar to the previous cases, an increase in upgrade magnitude causes an increase in the truck equivalency factor. This fact appears to be of significance for a total weight of full-trailer exceeding about 400 kN. At about 400 kN the curves in each chart start to diverge from each other indicating the importance of upgrade magnitude.



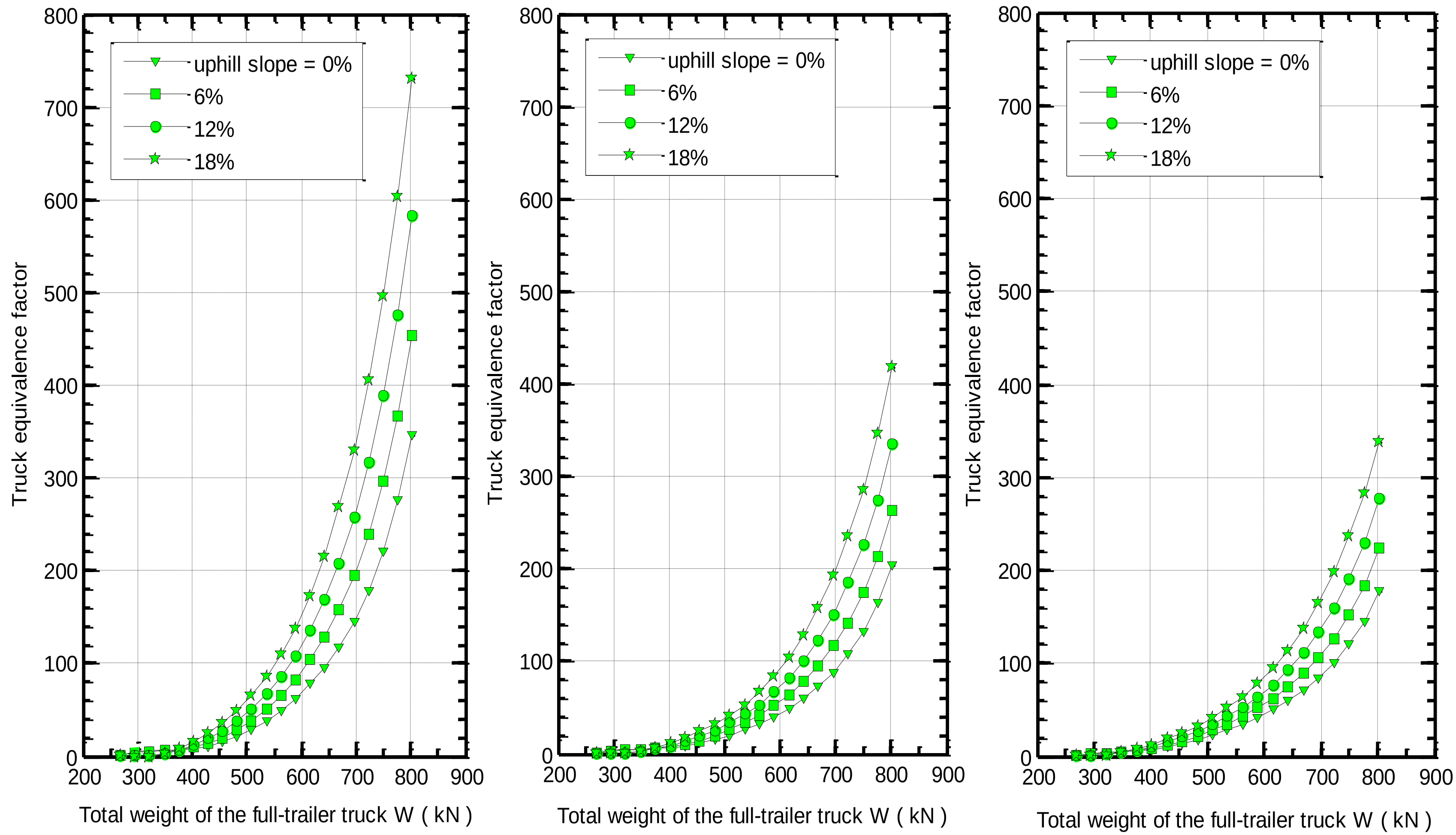
(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

Fig. (5.21) Truck equivalency factors for 11.2+2.2 full-trailers on uphill flexible pavements (case: H/B=0.2, p_t=2.5).



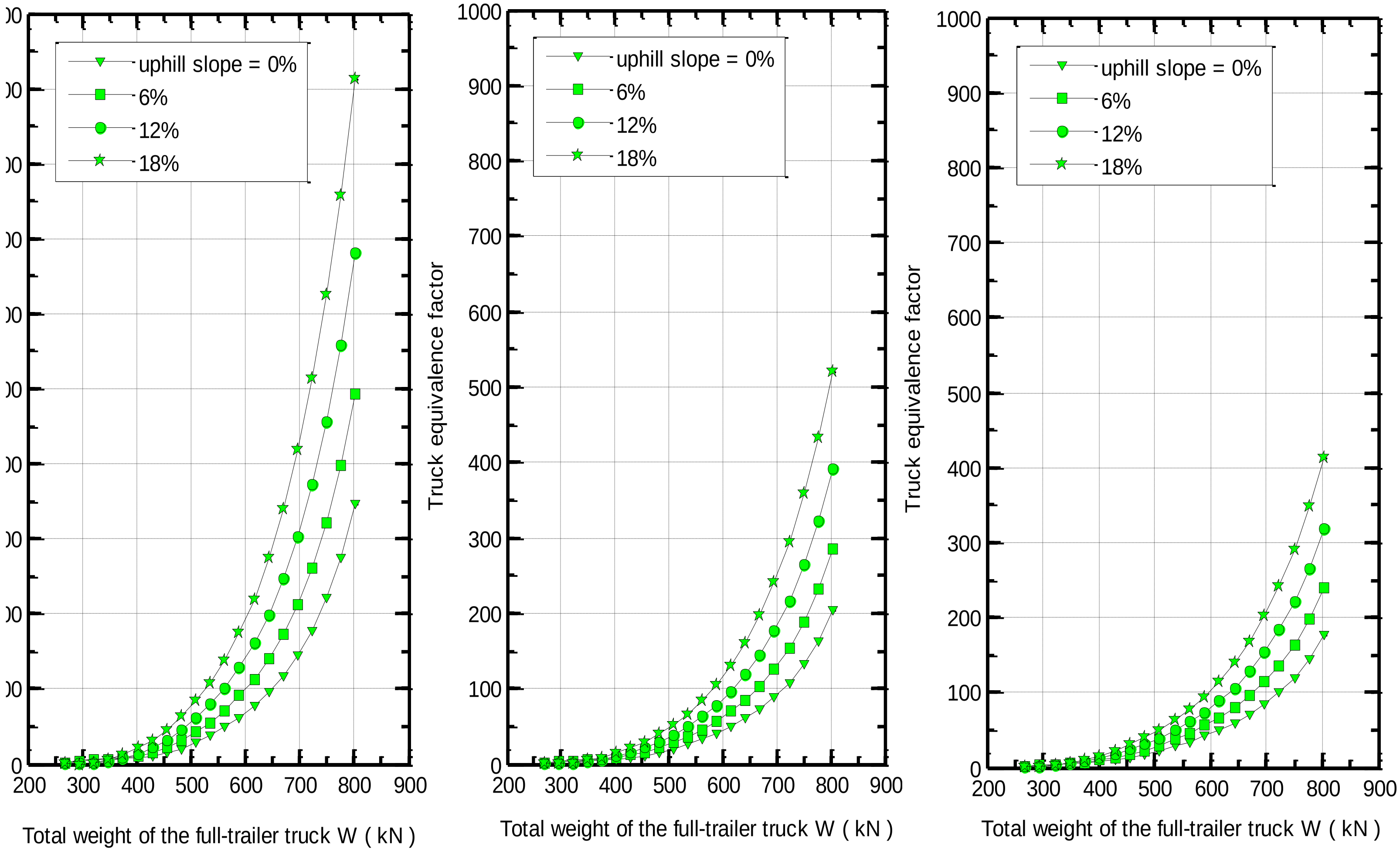
(A) SN = 2 (B) SN = 4 (C) SN = 6

Fig. (5.22) Truck equivalency factors for 11.2+2.2 full-trailers on uphill flexible pavements (case: H/B=0.4, p_t=2.5).



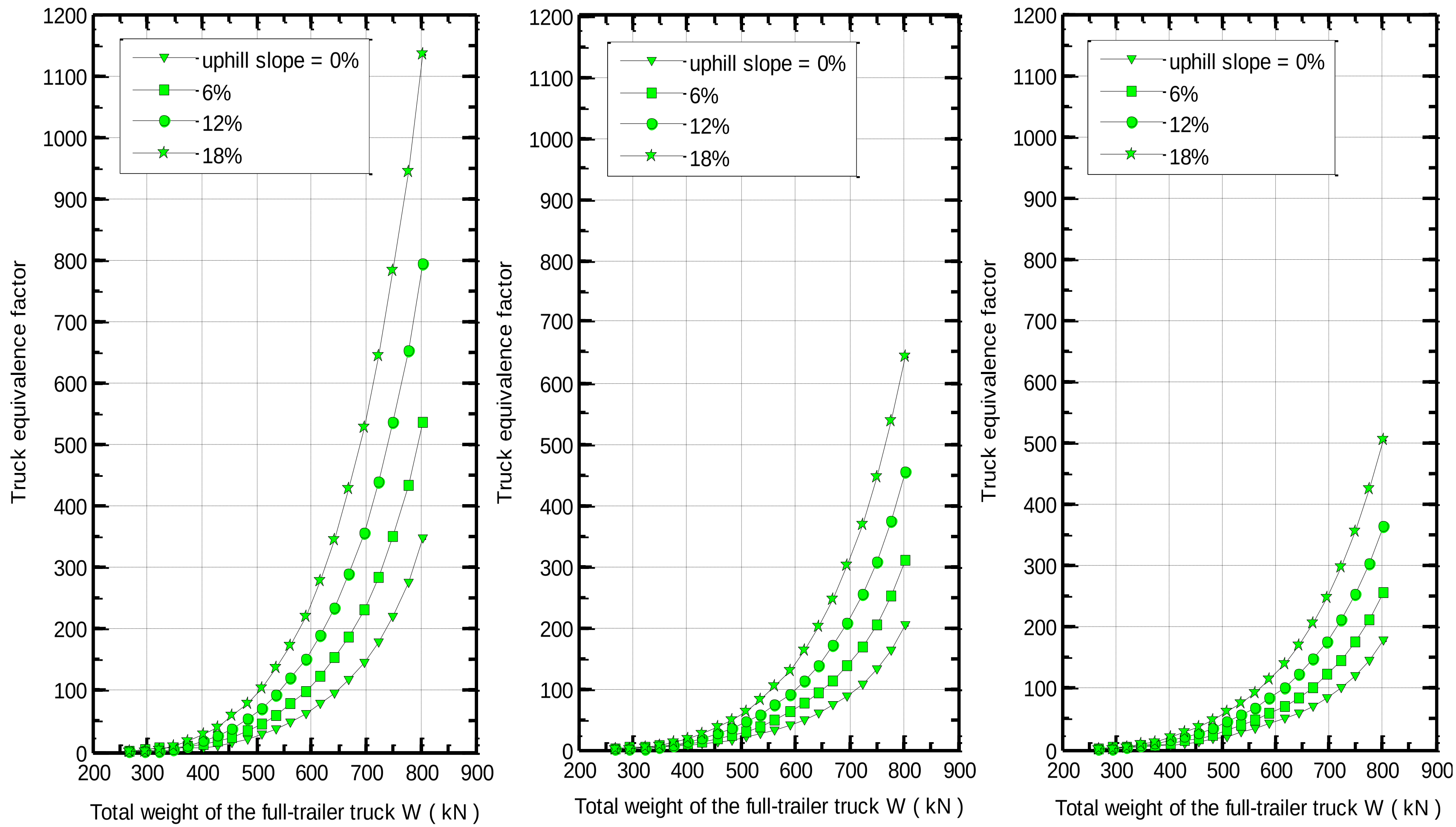
(A) SN = 2 (B) SN = 4 (C) SN = 6

Fig. (5.23) Truck equivalency factors for 11.2+2.2 full-trailers on uphill flexible pavements (case: H/B=0.6, p_t=2.5).



(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

Fig. (5.24) Truck equivalency factors for 11.2+2.2 full-trailers on uphill flexible pavements (case: H/B=0.8, p_t=2.5).



(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

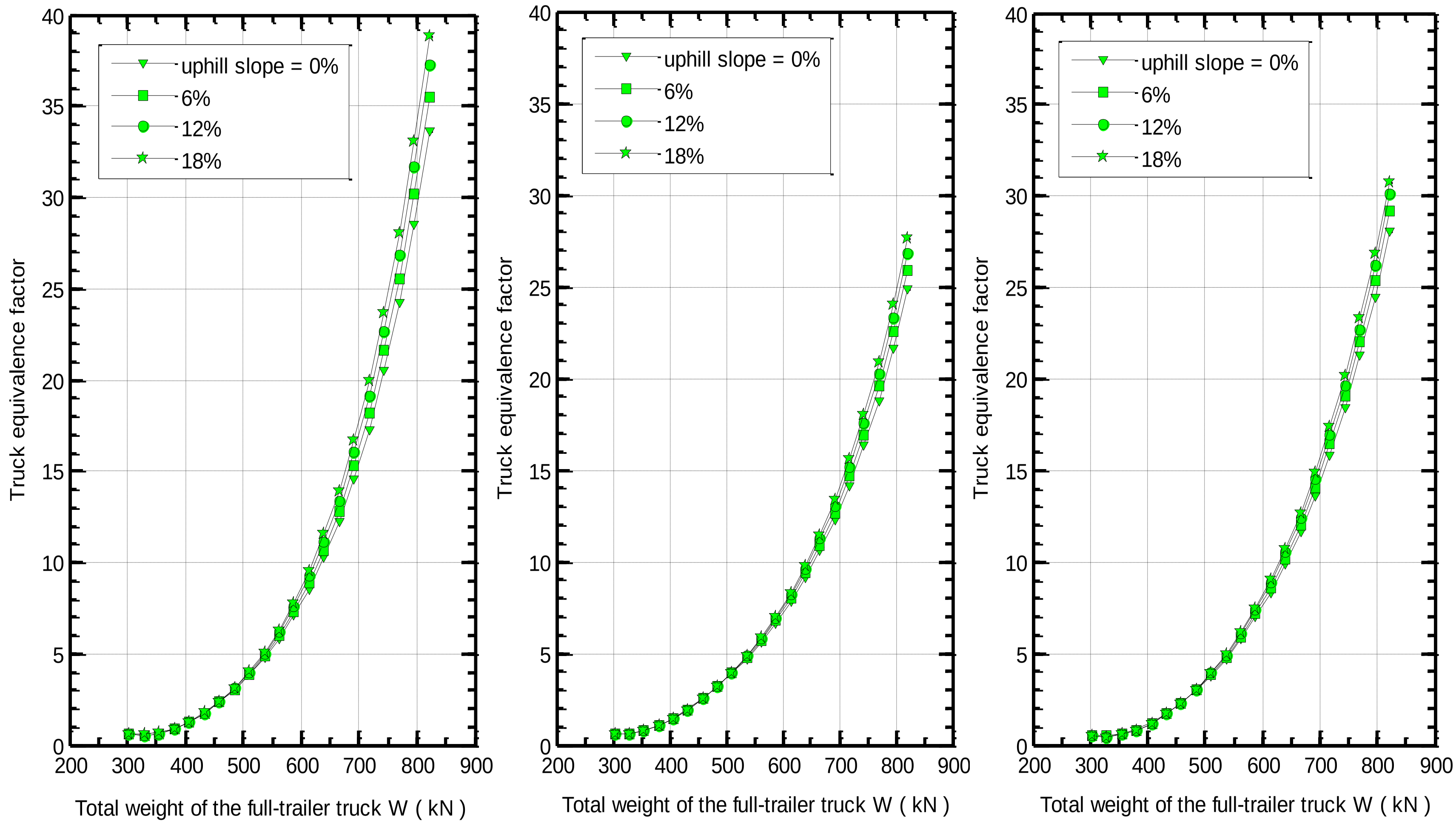
Fig. (5.25) Truck equivalency factors for 11.2+2.2 full-trailers on uphill flexible pavements (case: H/B=1, p_t=2.5).

5.2.6 Design Charts for 11.22+2.22 Full-Trailer

Figures (5.26 to 5.30) show the truck equivalency factors for full-trailer truck type 11.22+2.22 for the same values of SN, H/B ratio, and terminal level of serviceability adopted for type 1.2+2.2 full-trailer.

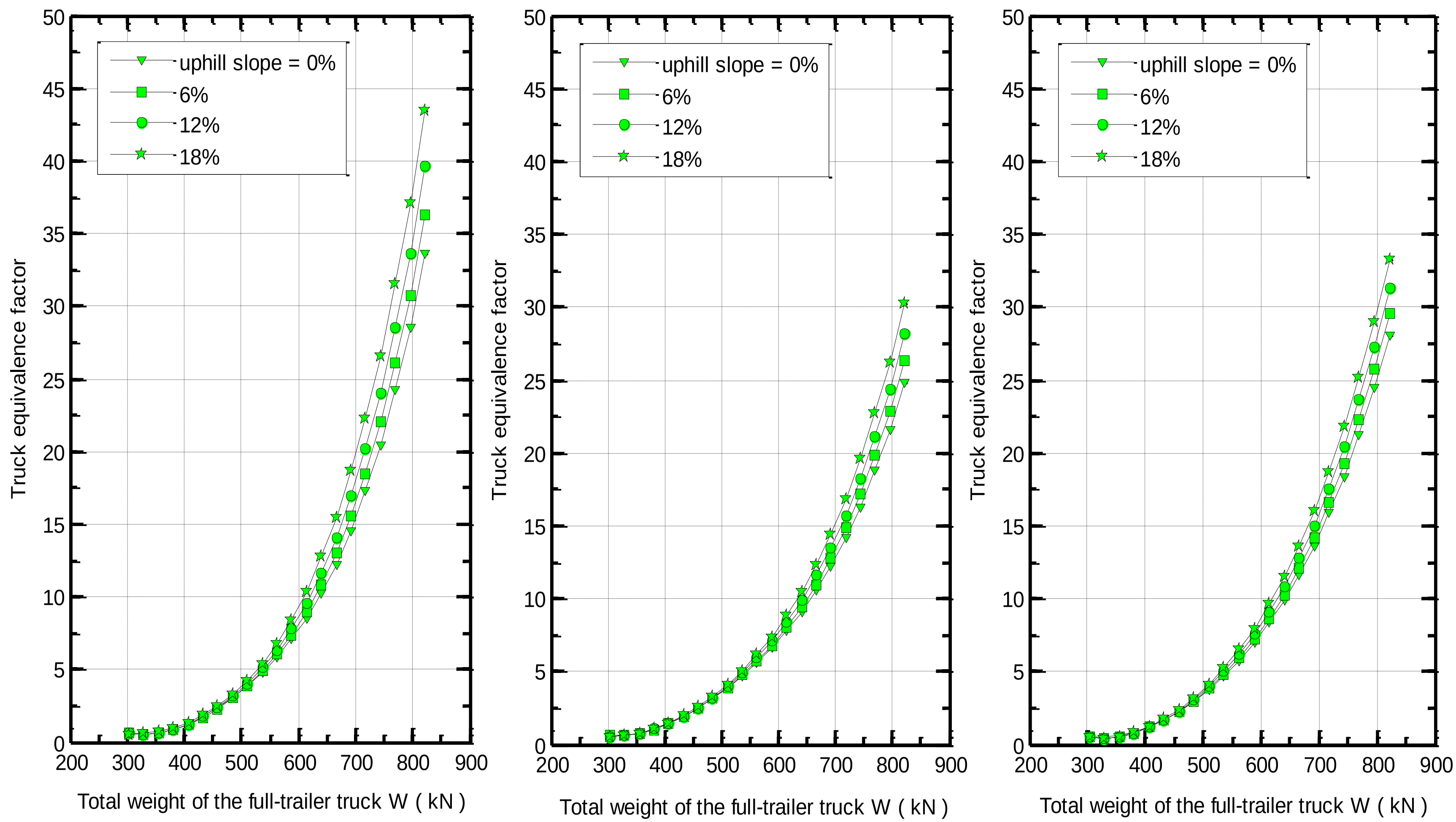
A thorough study of the whole design charts reveals that the effect of uphill slope on the truck equivalency factors becomes pronounced for truck weight exceeding about 500 kN indicating that this effect is of great importance for developing countries in which the phenomenon of overloading is very common.

In addition, the relatively low values of the truck equivalency factors indicate the importance of truck type as it will be discussed in section 5.3.



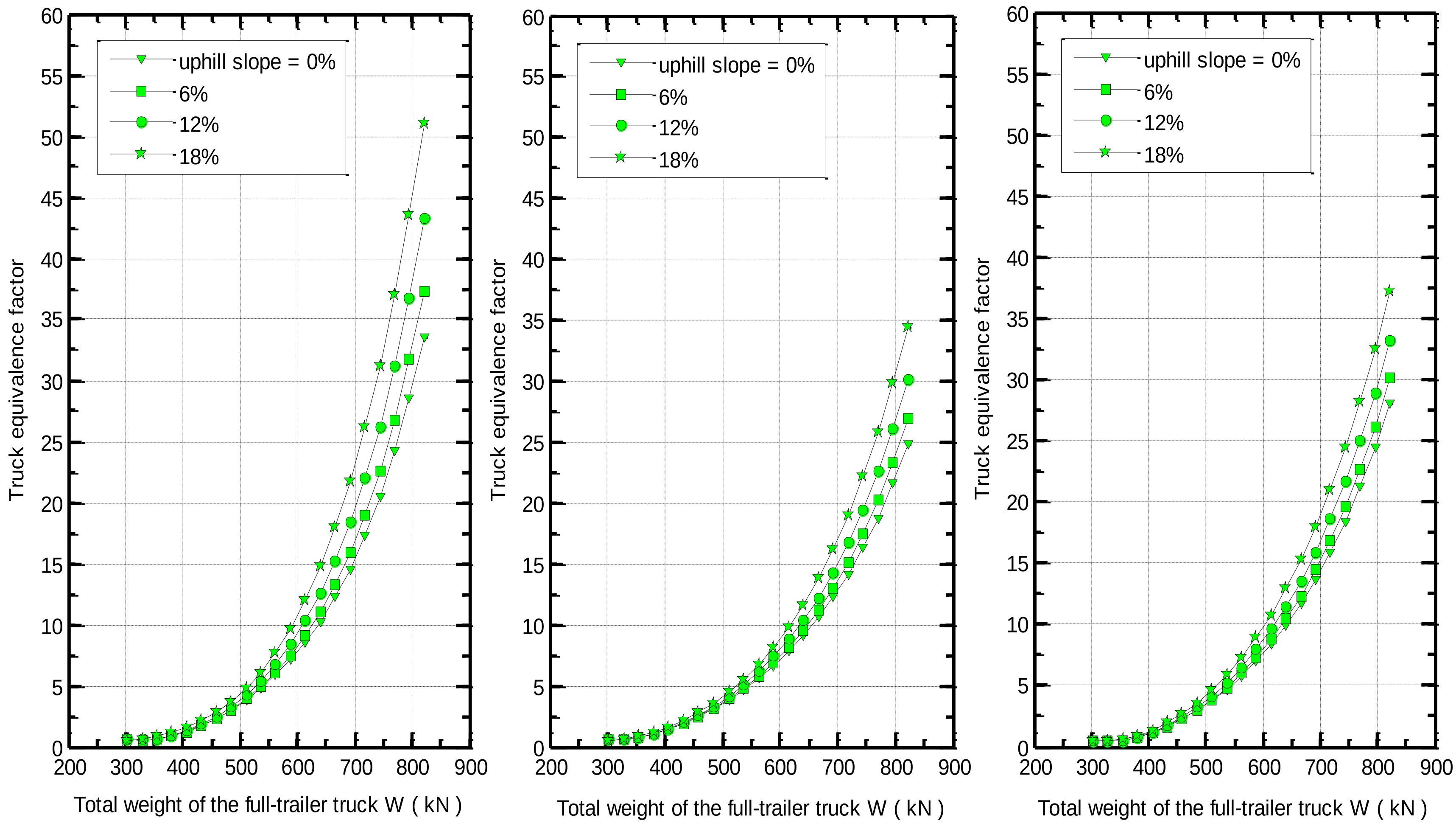
(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

Fig. (5.26) Truck equivalency factors for 11.22+2.22 full-trailers on uphill flexible pavements (case: H/B=0.2, p_t=2.5).



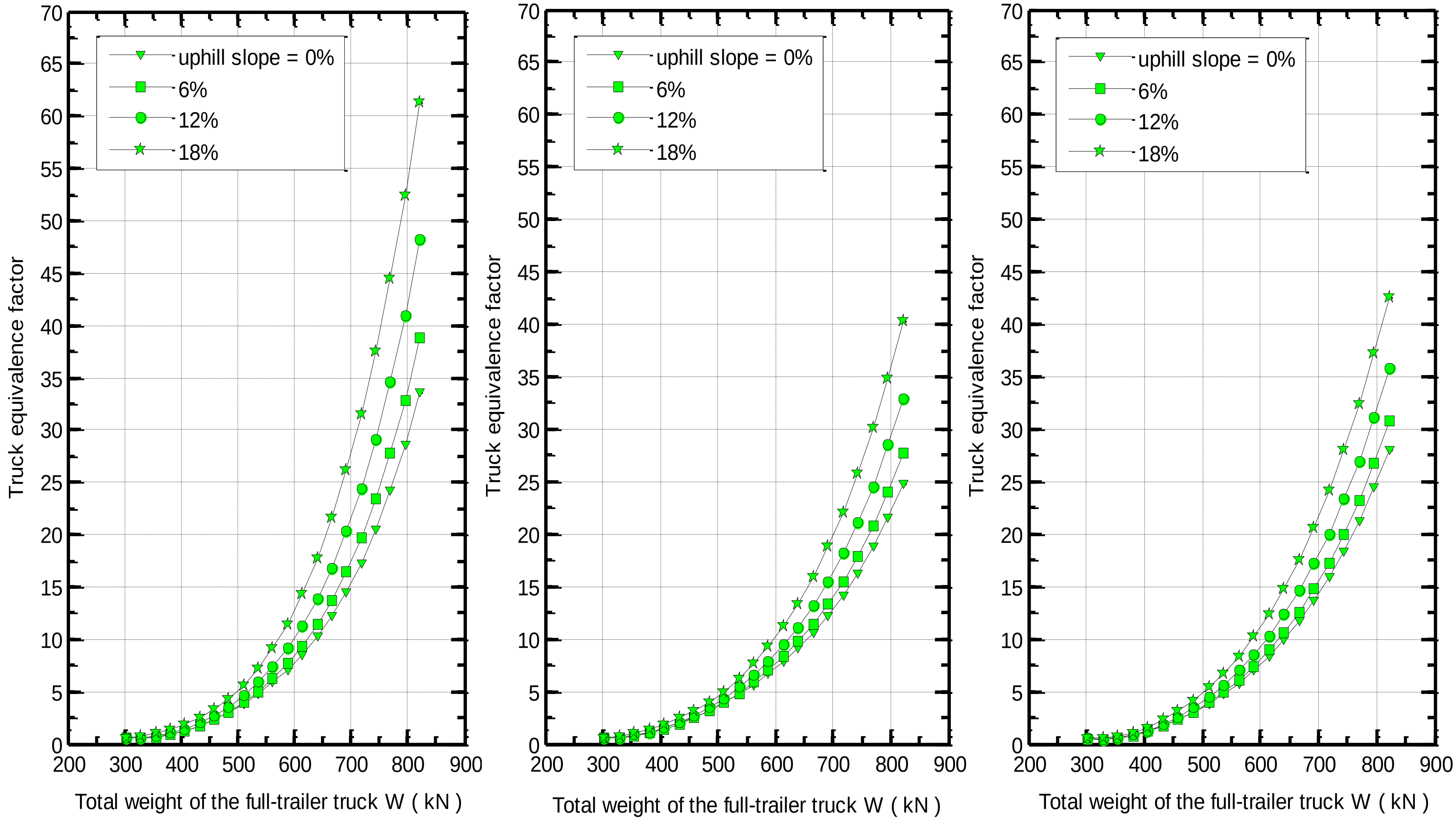
(A) SN = 2　**(B) SN = 4**　**(C) SN = 6**

Fig. (5.27) Truck equivalency factors for 11.22+2.22 full-trailers on uphill flexible pavements (case: H/B=0.4, p_t=2.5).



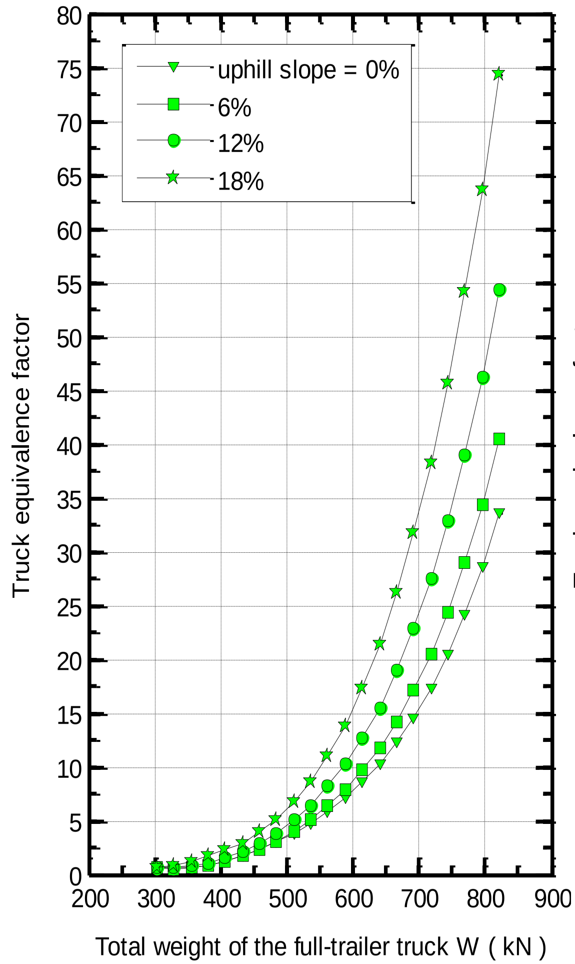
(A) SN = 2 **(B) SN = 4** **(C) SN = 6**

Fig. (5.28) Truck equivalency factors for 11.22+2.22 full-trailers on uphill flexible pavements (case: H/B=0.6, p_t=2.5).

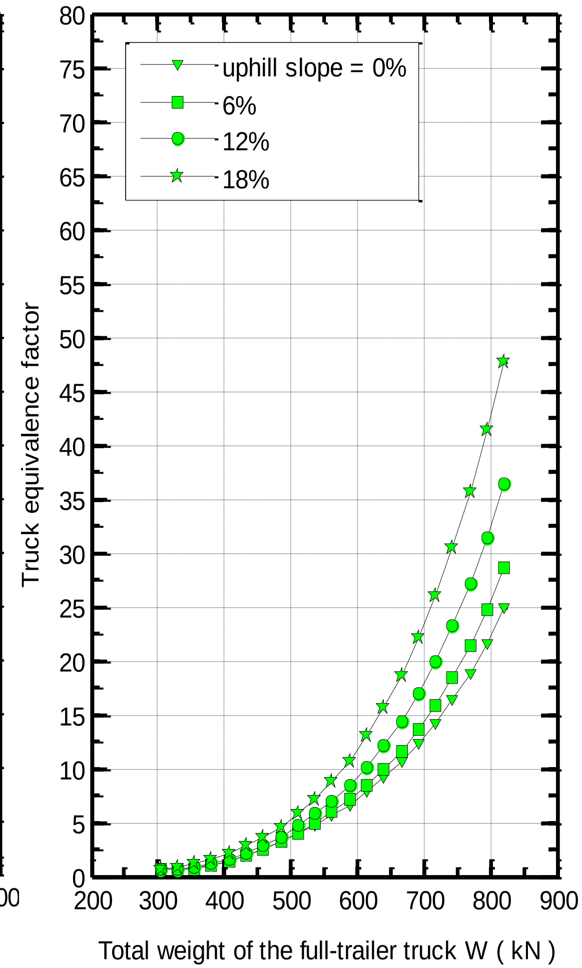


(A) SN = 2 (B) SN = 4 (C) SN = 6

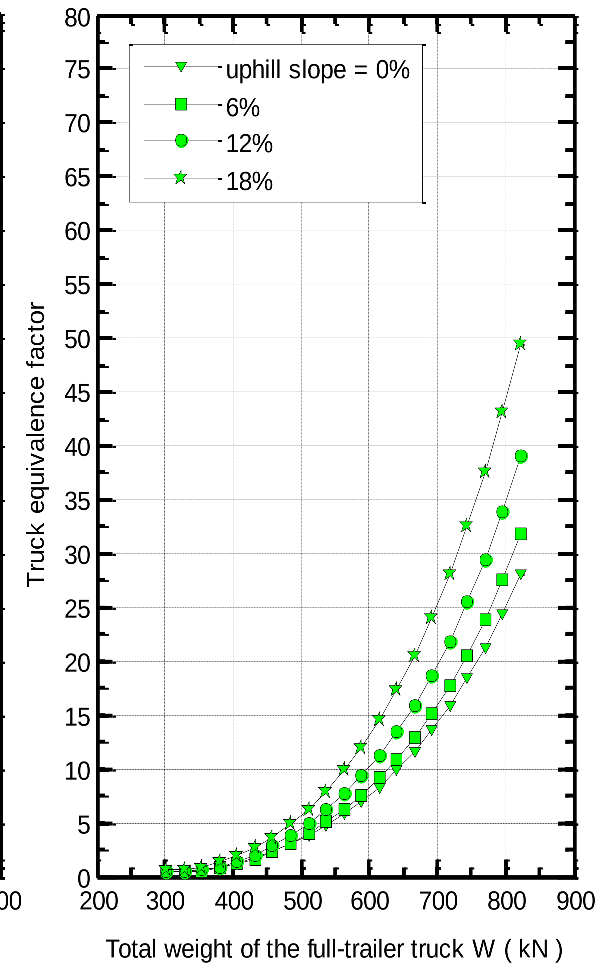
Fig. (5.29) Truck equivalency factors for 11.22+2.22 full-trailers on uphill flexible pavements (case: H/B=0.8, p_t=2.5).



(A) SN = 2



(B) SN = 4



(C) SN = 6

Fig. (5.30) Truck equivalency factors for 11.22+2.22 full-trailers on uphill flexible pavements (case: H/B=1, p_t=2.5).

5.3 Effect of Different Factors on the Full-Trailer Truck Equivalency Factor

After finding the truck equivalency factors on uphill pavements for different parameters, it is important to discuss in depth the effect of these parameters on the equivalency factors. For this purpose, the effect of type of full-trailer on the truck equivalency factor for different values of the structural number is to be studied first.

Figure (5.31) shows, for all six types of full-trailer trucks, the truck equivalency factor versus structural number for p_t=2.5, uphill slope of 12%, H/B of 1.0, and a total weight of full-trailer truck of 620 kN.

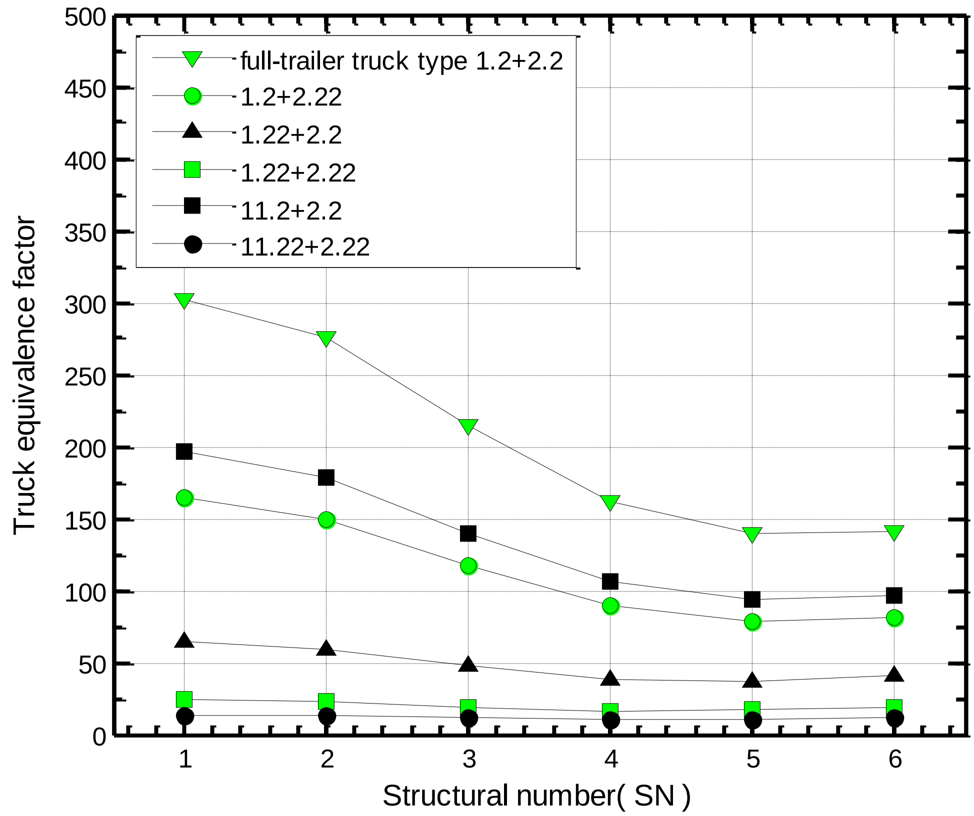


Fig. (5.31) Effect of type of full-trailer on truck equivalency factor …

p_t=2.5).

It is obvious from this figure that the truck equivalency factor (TEF) generally decreases with increasing structural number and that the type 1.2+2.2

full-trailer truck is the most damaging one. Also, it is obvious that the TEF for 1.22+2.2, 1.22+2.22 and 11.22+2.22 full-trailer truck types are slightly affected by the structural number, while this effect is clearly pronounced for 1.2+2.2, 1.2+2.22 and 11.2+2.2 full-trailer truck types. This is due to the fact mentioned previously that the maximum increase in the axle load will occur on the rear axle of the tractor (Rg_1) and the maximum decrease in the axle load will occur on the front axle of the same unit (Fg_1). This causes the increase in the equivalency factor (destructive effect) of Rg_1, which is much greater than the decrease resulting from Fg_1, especially when the rear axle of the tractor is a single axle.

The other very important factor affecting the full-trailer truck equivalency factor is the uphill gradient. Figure (5.32) shows the effect of uphill pavement slopes on the truck equivalency factors for all types of full-trailer trucks for SN=4, p_t=2.5, H/B =1.0, and a total weight of full-trailer truck of 620 kN.

It can be seen from Figure (5.32) that the uphill slope magnitude significantly affects the truck equivalency factors. This effect is clearly pronounced for full-trailer trucks type 1.2+2.2, 11.2+2.2 and 1.2+2.22. However, this effect is of little significance for full-trailer trucks type 1.22+2.2, 1.22+2.22 and 11.22+2.22.

For the 620 kN total weight of full-trailer truck and for H/B=1.0, p_t=2.5 and SN=4, the equivalency factor of full-trailer truck type 1.2+2.2 increases from 82.45 to 221.55 when the uphill slope increases from zero to 18% giving a ratio of 221.55/82.45=2.69 =269%.

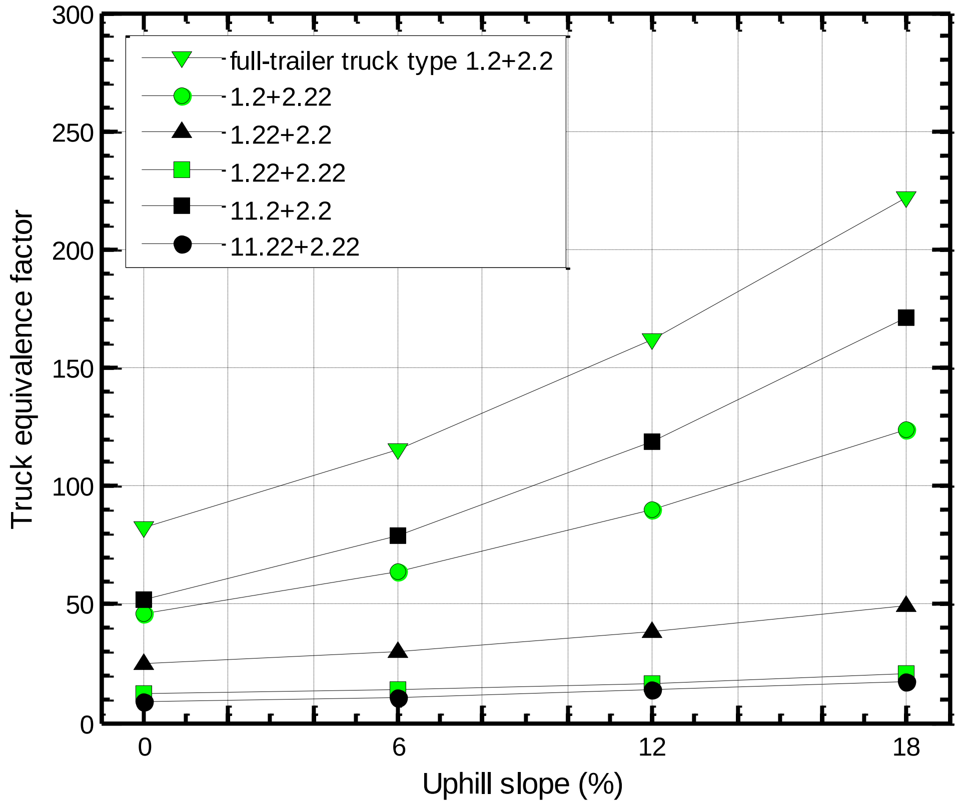


Fig. (5.32) Effect of uphill slope magnitude on truck equivalency factors for various types of full-trailers (case: H/B=1, SN =4, W =620 kN, p_t=2.5).

Note that this ratio becomes much more significant, namely 382.27/133.56=286% for SN=2 (see Figure (5.5), chart A). Similarly, for SN=4, this ratio becomes 123.89/46.29=267% (210.57/71.99=293% for SN=2), 49.59/24.74=201% (78.09/34.32=228% for SN=2), and 20.61/12.65=162% (29.10/15.32=190% for SN=2) for full-trailer types 1.2+2.22, 1.22+2.2, 1.22+2.22 respectively. However, for 11.2+2.2 full-trailer truck it increases to 171.13/51.72= 331% (293.66/81.11=362% for SN=2), while for full-trailer truck type 11.22+2.22, this ratio becomes 17.69/9.08 =195% (25.20/10.61=237% for SN=2).

Figure (5.33) shows the effect of H/B ratio on the truck equivalency factors for all types of full-trailer trucks mentioned before, uphill slope of 12%, a total load of the full-trailer truck of 620 kN, p_t of 2.5, and SN of 4.

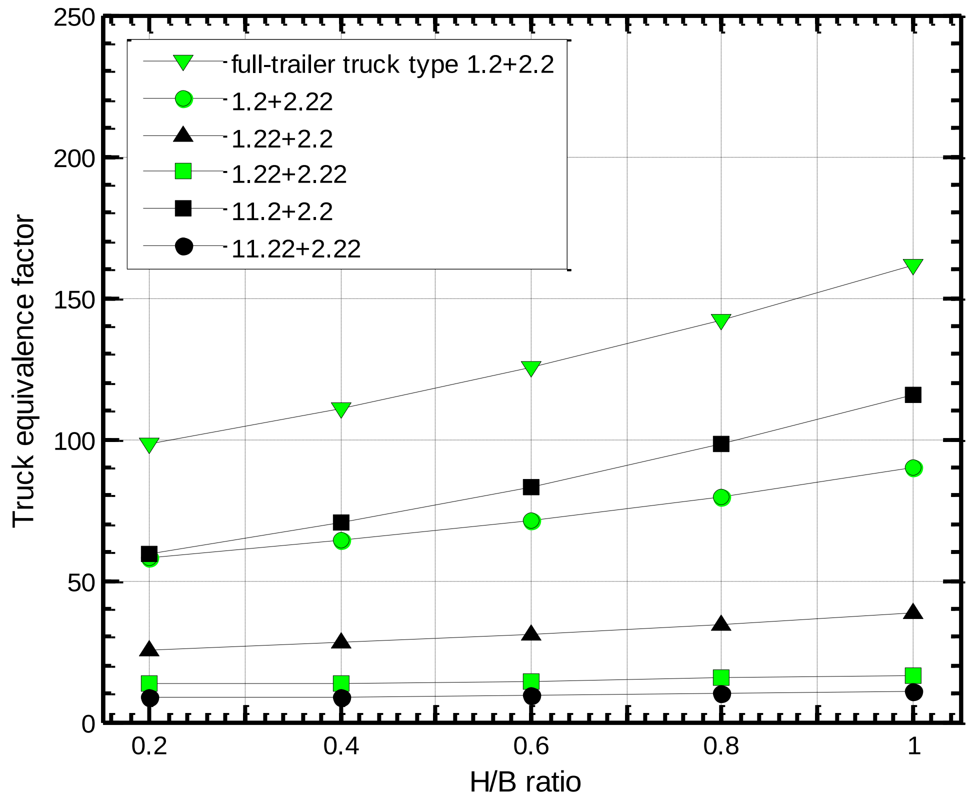


Fig. (5.33) Effect of H/B ratio on truck equivalency factors for various types of full-trailers (case: SN=4, uphill slope =12%, W =620 kN, p_t=2.5).

It is clear from this figure that the truck equivalency factor increases most rapidly with increasing H/B ratio for full-trailer type 1.2+2.2, 11.2+2.2 and 1.2+2.22. While for full-trailer truck type 1.22+2.2, 1.22+2.22 and 11.22+2.22 the increase is less significance due to the same reasons mentioned in connection with Figure (5.31).

Figure (5.34) shows the effect of terminal level of serviceability (p_t) on the truck equivalency factors for all types of full-trailer trucks mentioned before, H/B=1, uphill slope of 12%, a total load of the full-trailer of 620 kN, and SN of 4.

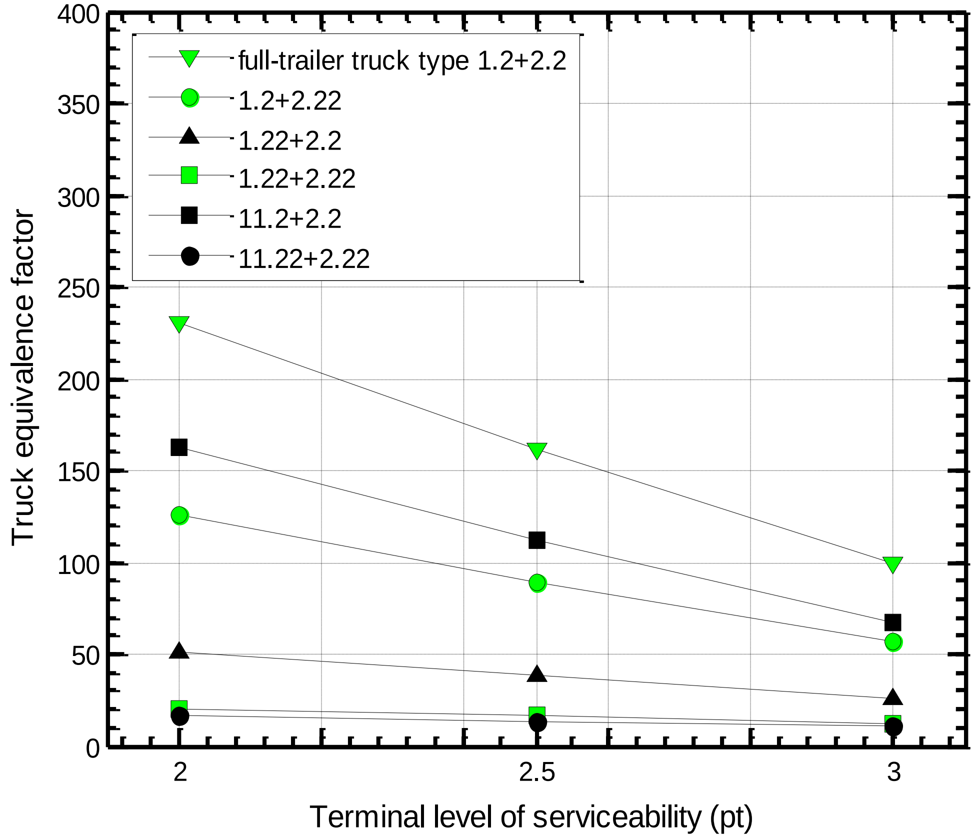


Fig. (5.34) Effect of terminal level of serviceability on truck equivalency factors for various types of full-trailers (case: H/B=1, uphill slope =12%, W=620 kN, SN=4).

It is obvious from this figure that the truck equivalency factor decreases with increasing magnitude of p_t. This effect of p_t is pronounced in connection with full-trailer truck type 1.2+2.2, 1.2+2.22, 11.2+2.2, and 1.22+2.2, while it becomes insignificant for the case of full-trailer type 1.22+2.22 and11.22+2.22.

5.4 <u>Average Truck Equivalency Factors</u>

To simplify the design process, Tables (5.1) through (5.6) present the average truck equivalency factors of full-trailer truck type 1.2+2.2, 1.2+2.22, 1.22+2.2, 1.22+2.22, 11.2+2.2, and 11.22+2.22, respectively, for terminal level of serviceability (p_t) of 2.5. However, the average truck equivalency factors of full-trailer truck type 1.2+2.2, 1.2+2.22, 1.22+2.2, 1.22+2.22, 11.2+2.2, and 11.22+2.22 for p_t of 2 are shown in Appendix (F).

Table (5.1) Average truck equivalency factors for full-trailer trucks of type 1.2+2.2 for p_t=2.5.

H/B	Uphill slope (%)	Structural Number, SN					
		1	2	3	4	5	6
0.2	0	49.00	45.07	36.48	29.60	28.09	30.17
	6	55.10	50.59	40.73	32.71	30.70	32.80
	12	61.08	56.01	44.89	35.74	33.23	35.31
	18	66.71	61.11	48.79	38.56	35.57	37.61
0.4	0	49.00	45.07	36.48	29.60	28.09	30.17
	6	58.74	53.90	43.27	34.58	32.28	34.39
	12	69.56	63.70	50.81	40.09	36.91	38.99
	18	81.06	74.12	58.81	45.94	41.80	43.80
0.6	0	49.00	45.07	36.48	29.60	28.09	30.17
	6	62.73	57.51	46.06	36.62	34.02	36.13
	12	79.49	72.70	57.74	45.18	41.22	43.28
	18	98.80	90.20	71.20	55.06	49.49	51.39
0.8	0	49.00	45.07	36.48	29.60	28.09	30.17
	6	67.07	61.45	49.08	38.85	35.90	38.03
	12	90.94	83.08	65.74	51.07	46.18	48.21
	18	120.27	109.66	86.21	66.09	58.76	60.48
1.0	0	49.00	45.07	36.48	29.60	28.09	30.17
	6	71.77	65.71	52.37	41.26	37.94	40.07
	12	104.02	94.94	74.87	57.79	51.84	53.80
	18	145.84	132.85	104.09	79.23	69.75	71.20

Table (5.2) Average truck equivalency factors for full- trailer trucks of type 1.2+2.22 for p_t=2.5.

H/B	Uphill slope (%)	Structural Number, SN					
		1	2	3	4	5	6
0.2	0	71.95	65.91	52.62	41.53	38.12	40.06
	6	83.15	76.06	60.42	47.21	42.83	44.64
	12	94.59	86.43	68.38	53.00	47.61	49.24
	18	105.81	96.59	76.17	58.66	52.25	53.68
0.4	0	71.95	65.91	52.62	41.53	38.12	40.06
	6	87.88	80.34	63.71	49.60	44.78	46.48
	12	106.04	96.80	76.34	58.79	52.35	53.72
	18	125.82	114.72	90.10	68.80	60.57	61.51
0.6	0	71.95	65.91	52.62	41.53	38.12	40.06
	6	93.12	85.09	67.35	52.24	46.95	48.54
	12	119.65	109.13	85.82	65.69	58.01	59.08
	18	150.91	137.45	107.58	81.55	71.04	71.38
0.8	0	71.95	65.91	52.62	41.53	38.12	40.06
	6	98.88	90.31	71.36	55.16	49.34	50.81
	12	135.48	123.47	96.84	73.72	64.62	65.34
	18	181.34	.03	128.79	97.03	83.77	83.38
1.0	0	71.95	65.91	52.62	41.53	38.12	40.06
	6	105.17	96.00	75.73	58.34	51.95	53.30
	12	153.61	139.90	109.47	82.94	72.22	72.53
	18	217.49	197.79	154.00	115.43	98.90	97.62

Table (5.3) Average truck equivalency factors for full-trailer trucks of type 1.22+2.2 for p_t=2.5.

H/B	Uphill slope (%)	Structural Number, SN					
		1	2	3	4	5	6
0.2	0	27.55	25.59	21.37	18.28	18.20	19.93
	6	28.47	26.42	21.99	18.71	18.56	20.32
	12	29.18	27.05	22.46	19.02	18.80	20.60
	18	29.62	27.44	22.73	19.17	18.91	20.72
0.4	0	27.55	25.59	21.37	18.28	18.20	19.93
	6	29.76	27.58	22.89	19.36	19.13	20.94
	12	32.24	29.83	24.59	20.59	20.19	22.10
	18	34.80	32.14	26.34	21.85	21.30	23.30
0.6	0	27.55	25.59	21.37	18.28	18.20	19.93
	6	31.27	28.96	23.94	20.14	19.80	21.67
	12	36.18	33.40	27.33	22.62	21.98	24.02
	18	41.88	38.56	31.29	25.56	24.57	26.77
0.8	0	27.55	25.59	21.37	18.28	18.20	19.93
	6	33.02	30.54	25.15	21.03	20.58	22.51
	12	41.02	37.78	30.71	25.13	24.20	26.37
	18	50.95	46.78	37.65	30.32	28.74	31.14
1.0	0	27.55	25.59	21.37	18.28	18.20	19.93
	6	34.99	32.33	26.53	22.04	21.47	23.46
	12	46.76	42.99	34.73	28.14	26.83	29.14
	18	62.15	56.94	45.52	36.19	33.84	36.42

Table (5.4) Average truck equivalency factors for full- trailer trucks of type 1.22+2.22 for p_t=2.5.

H/B	Uphill slope (%)	Structural Number, SN					
		1	2	3	4	5	6
0.2	0	17.10	16.11	14.06	12.76	13.07	14.11
	6	17.91	16.85	14.61	13.15	13.43	14.53
	12	18.66	17.52	15.10	13.49	13.74	14.91
	18	19.28	18.07	15.50	13.76	13.98	15.20
0.4	0	17.10	16.11	14.06	12.76	13.07	14.11
	6	18.10	17.02	14.72	13.22	13.50	14.62
	12	19.39	18.18	15.59	13.84	14.07	15.29
	18	20.83	19.47	16.56	14.55	14.72	16.04
0.6	0	17.10	16.11	14.06	12.76	13.07	14.11
	6	18.46	17.34	14.96	13.38	13.64	14.80
	12	20.72	19.38	16.50	14.52	14.70	16.02
	18	23.63	22.00	18.51	16.03	16.10	17.59
0.8	0	17.10	16.11	14.06	12.76	13.07	14.11
	6	18.97	17.79	15.30	13.63	13.87	15.06
	12	22.61	21.08	17.80	15.50	15.62	17.06
	18	27.57	25.57	21.28	18.13	18.05	19.77
1.0	0	17.10	16.11	14.06	12.76	13.07	14.11
	6	19.62	18.39	15.75	13.96	14.18	15.42
	12	25.01	23.26	19.49	16.78	16.81	18.41
	18	32.60	30.14	24.82	20.84	20.55	22.55

Table (5.5) Average truck equivalency 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	141.81	129.46	102.23	79.15	71.36	74.52
	6	159.56	145.55	114.60	88.18	78.79	81.64
	12	177.16	161.49	126.86	97.08	86.08	88.54
	18	193.96	176.72	138.54	105.55	92.97	95.00
0.4	0	141.81	129.46	102.23	79.15	71.36	74.52
	6	174.03	158.67	124.70	95.54	84.86	87.46
	12	210.18	191.43	149.89	113.87	99.89	101.72
	18	249.26	226.84	177.10	133.65	116.07	116.93
0.6	0	141.81	129.46	102.23	79.15	71.36	74.52
	6	189.76	172.93	135.67	103.54	91.44	93.76
	12	248.73	226.37	176.77	133.46	115.99	117.00
	18	317.98	289.12	225.00	168.55	144.69	143.92
0.8	0	141.81	129.46	102.23	79.15	71.36	74.52
	6	206.81	188.38	147.56	112.20	98.57	100.57
	12	293.33	266.79	207.85	156.10	134.57	134.56
	18	401.99	365.27	283.55	211.19	179.60	176.64
1.0	0	141.81	129.46	102.23	79.15	71.36	74.52
	6	225.24	205.08	160.41	121.57	106.27	107.90
	12	344.53	313.20	243.54	182.10	155.88	154.60
	18	503.42	457.18	354.21	262.64	221.64	215.80

Table (5.6) Average truck equivalency 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	17.26	16.25	14.12	12.67	12.85	13.87
	6	18.65	17.52	15.09	13.39	13.49	14.60
	12	20.00	18.74	16.02	14.06	14.09	15.27
	18	21.25	19.86	16.86	14.65	14.60	15.86
0.4	0	17.26	16.25	14.12	12.67	12.85	13.87
	6	19.39	18.19	15.60	13.75	13.81	14.95
	12	21.95	20.50	17.37	15.04	14.95	16.22
	18	24.83	23.11	19.35	16.48	16.22	17.63
0.6	0	17.26	16.25	14.12	12.67	12.85	13.87
	6	20.29	19.00	16.22	14.20	14.21	15.39
	12	24.54	22.85	19.17	16.36	16.13	17.52
	18	29.84	27.65	22.84	19.08	18.54	20.14
0.8	0	17.26	16.25	14.12	12.67	12.85	13.87
	6	21.34	19.95	16.95	14.74	14.68	15.92
	12	27.76	25.76	21.41	18.03	17.62	19.14
	18	36.31	33.52	27.37	22.47	21.57	23.39
1.0	0	17.26	16.25	14.12	12.67	12.85	13.87
	6	22.55	21.05	17.79	15.36	15.23	16.53
	12	31.63	29.27	24.11	20.05	19.43	21.11
	18	44.32	40.78	32.98	26.69	25.33	27.38

5.5 Effect of Uphill Slope on Pavement Thickness

AASHTO load equivalency factors are known for level highways. However, on site, there are different slopes for uphill pavements. This uphill slope redistributes the axle loads as mentioned before. This redistribution of load among axles will eventually lead to increasing the damaging effect on highway pavements as shown by the charts presented under section (5.2). This, in turn, results in increasing the thickness required to satisfy the design life of the pavement.

To display the effect of increased damage to flexible pavements caused by full-trailer trucks on uphill slopes, the case of a flexible pavement of a road serving specialized traffic will be studied thoroughly.

In developing and developed countries, many of such highways lead to silos, asphalt mixing plants, certain factories, concrete mixing plants, stores, etc. For this reason, the same case investigated by Razouki and Radeef (2005) will be considered. This case deals with the design of a flexible pavement for a level highway to serve 2×10^6 equivalent standards (18 kips) single-axle load applications during its design period. The pavement is assumed to consist of only two layers (surface and base) resting on a roadbed soil. The characteristics of flexible pavement layers are summarized as shown in Table (5.7).

Table (5.7) The characteristics of flexible pavement layers (after Yoder and Witczak, 1975).

	Layer coefficient (a)	Drainage coefficient (m)	Resilient modulus (M_R) (Psi)
Asphalt concrete surfacing	0.43	1.00	N/A
Granular base	0.182	0.80	45000
Subgrade	N/A	N/A	9000

Note: 1 Psi = 6.8947572 kPa.

For the initial level of serviceability of 4.2 and a terminal level of serviceability of p_t =2, the loss in serviceability becomes ΔPSI=2.5.

Using AASHTO Guide (1993) equation given by equation (5.1), the structural number above the roadbed soil required on a level section of the road can be calculated:

$$\begin{aligned}\mathbf{log_{10}(W_{18}) = Z_R \times S_O + 9.36 \times log_{10}(SN+1) - 0.2 + A/B} \\ \mathbf{+ 2.32 \times log_{10}(MR) - 8.07}\end{aligned} \qquad \textbf{(5.1)}$$

where:

$\mathbf{A = log_{10}\ (\Delta PSI/(4.2 - 1.5)) \ = \ log_{10}\ (\Delta PSI/2.7)}$

$\mathbf{B = 0.4 + 1094/(SN+1)^{5.19}}$

$\mathbf{W_{18}}$ = number of 18-kip equivalent single axle load applications.

$\mathbf{Z_R}$ = standard normal deviate.

So = combined standard error of the traffic prediction and performance prediction.

Δ**PSI** = difference between the initial design serviceability index (p_o), and the design terminal serviceability index (p_t).

MR = resilient modulus (psi).

SN = structural number as given by equation (2.1).

For a combined standard error of the performance and traffic prediction of S_O = 0.45 and a standard normal deviate of Z_R = -2.327 (for R=99%) (AASHTO Guide, 1993), equations (5.1) can be written as follows:

$$\begin{aligned}\mathbf{log_{10}(W_{18}) = 9.31715 + 9.36 \times log_{10}(SN+1) - 0.03342/B} \\ \mathbf{+ 2.32 \times log_{10}(MR)}\end{aligned} \qquad \textbf{(5.2)}$$

Six scenarios will be investigated. In the first one, it is expected that throughout the design period of the level section, the road is subjected to 2×10^6 standard single axle load applications due to 1.2+2.2 full-trailer trucks only.

By using equations (5.2) and (2.1), the thickness design of level flexible pavement layers can be summarized in Figure (5.35).

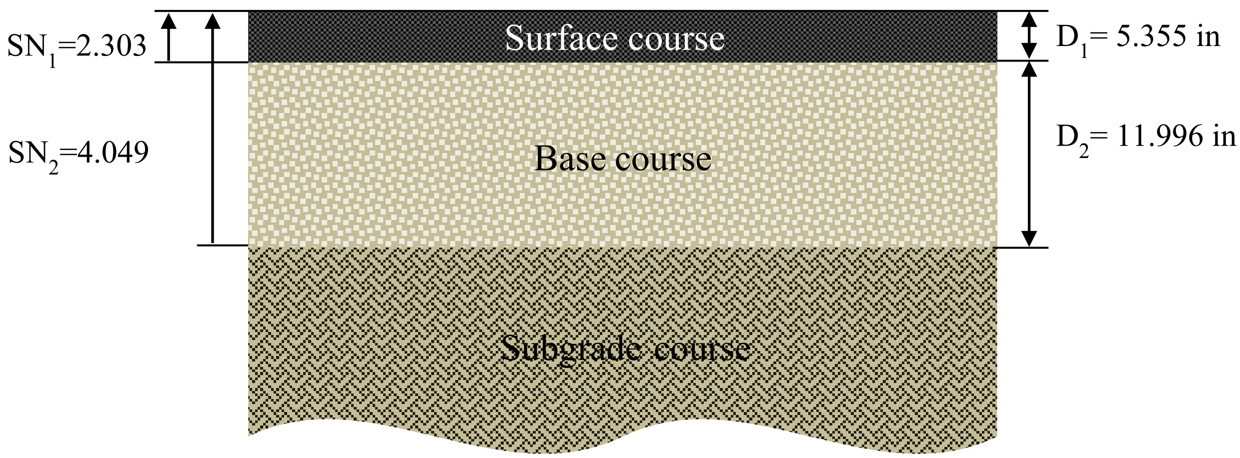


Fig. (5.35) The design of level flexible pavement layers.

The axle load survey carried out by Al-Muhanna (2008) revealed that the average weight of mixed loaded and empty 1.2+2.2 full-trailer trucks was about 450 kN.

For the determined structural number above, the subgrade SN_2=3.941≈4, p_t=2 and H/B=1.0, the ratio of the TEF on 12% upgrade to that for a level highway is 56.01/27.48=2.038 (see Appendix F, Table (F.7)). Therefore, this means that the 12% uphill pavement should be designed for $2.038\times2\times10^6 = 4.077\times10^6$ standard single axle load applications.

By using equations (5.2) and (2.1), the thickness design of 12% uphill flexible pavement layers can be summarized in Figure (5.36).

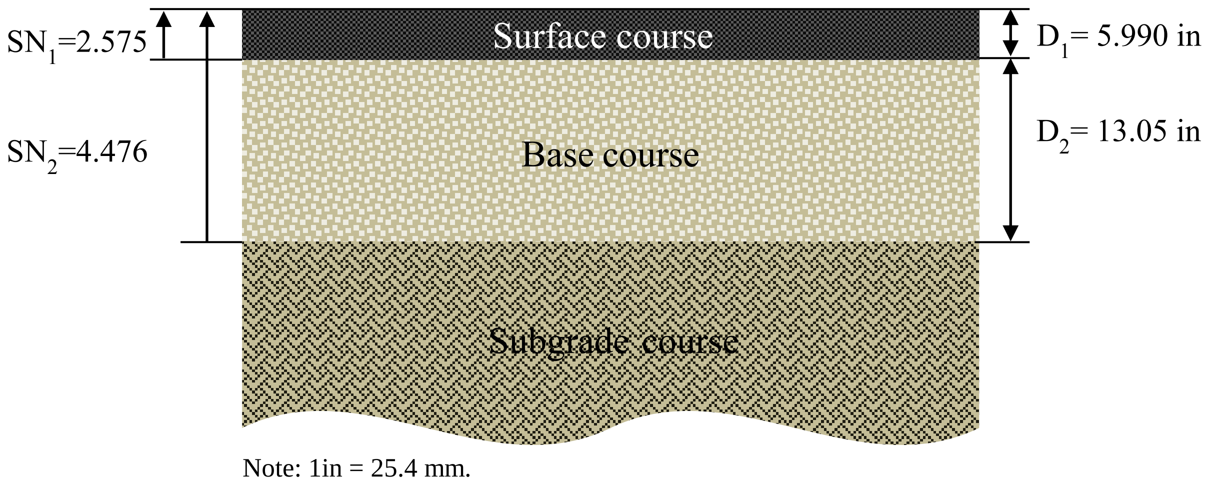


Fig. (5.36) The design of 12% uphill flexible pavement layers.

If the same thickness of 5.990 in (152.15mm) for surfacing is chosen for both level as well as uphill pavement, then the thickness of base for level highway becomes 10.12 in (257.07mm) and for the uphill pavement remains 13.054in (331.57mm). Hence, the effect of uphill gradient on pavement thickness is relatively obvious, and it is exhibited through an increase in base thickness of 2.93in (74.42mm).

In a similar manner, the pavement layer thicknesses on both level and uphill flexible pavements for rising grades of 6% and 18% were calculated and tabulated for all uphill slopes in Table (5.8).

Table (5.8) Effect of uphill slope on increasing pavement thickness (case; 1.2+2.2 full-trailer truck, p_t=2.0)

Uphill slope (%)	Surface layer thickness for both level and uphill pavement (mm)	Base layer thickness of level pavement (mm)*	Base layer thickness of uphill pavement (mm)	The increase in base thickness from that on level Highway (mm)
6	143.84	281.69	317.88	36.19
12	152.15	257.07	331.57	74.42
18	160.25	233.17	344.40	111.23

*thickness of base layer for the same surface layer thickness on uphill slope.

It is worth mentioning that instead of depending on the average weight of full-trailer trucks for determining the equivalent number of standard single axle load repetitions on the uphill pavement, the use of the average truck equivalency factor is also possible. For this purpose, this method was applied to the first scenario discussed above and the results obtained were completely the same as when using the average weight of the full-trailer truck. Therefore, only the method of the average weight of full-trailer truck will be applied in connection with the remaining truck types.

The second, third, fourth, fifth and sixth scenarios are devoted to truck types1.2+2.22, 1.22+2.2, 1.22+2.22, 11.2+2.2, and 11.22+2.22 respectively. According to data obtained from Al-Muhanna (2008) and the axle load survey in this study and Table (F.7) (see Appendix F), the average weights of these trucks are 538kN, 523kN, 600kN, 645kN and 660kN respectively. Table (5.9) summarizes the pavement results obtained in the same way as mentioned under the first scenario.

It is clear that the effect of uphill gradient on pavement thickness is more pronounced in the case of 1.2+2.2, 1.2+2.22, and 11.2+2.2 full-trailer trucks than in the case of 1.22+2.2, 1.22+2.22, and 11.22+2.22 full-trailer trucks.

Table (5.9) Effect of uphill slope on increasing pavement thickness (case: 1.2+2.22, 1.22+2.2, 1.22+2.22,11.2+2.2,11.22+2.22 full-trailer trucks, p_t=2.0)

Full-trailer truck type	Uphill slope (%)	Surface layer thickness for both level and uphill pavement (mm)	Base layer thickness of level pavement (mm)*	Base layer thickness of uphill pavement (mm)	The increase in base thickness from that on level Highway (mm)
1.2+2.22	6	143.69	263.16	317.68	54.52
	12	151.97	238.72	331.24	92.52
	18	160.02	214.92	344.07	129.15
1.22+2.2	6	140.94	271.2	313.05	41.85
	12	147.19	252.81	323.44	70.63
	18	153.54	234.04	333.81	99.77
1.22+2.22	6	138.46	278.65	308.79	30.14
	12	143.05	265.06	316.53	51.37
	18	148.39	249.29	325.37	76.08
11.2+2.2	6	146.23	255.62	321.84	66.22
	12	156.29	225.93	338.18	112.25
	18	165.79	197.88	353.03	155.15
11.22+2.2 2	6	140.69	271.97	312.62	40.66
	12	147.60	251.64	324.08	72.43
	18	155.12	229.39	336.30	106.92

*thickness of base layer for the same surface layer thickness on uphill slope.

6

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

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CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Based on the results obtained from this thesis, the following conclusions can be drawn:

1) The maximum axle loads of full-trailer trucks appeared in this work exceeded greatly the legal axle load limits in Iraq. The maximum axle loads obtained from the surveys were 12.320, 21.990, 28.320and 34.580 tonnes (120.86, 215.51, 277.82and 339.23kN) for front single, front tandem, rear single, and rear tandem axles, respectively. These observed maximum axle loads are 176, 218, and 173 percent time their legal limits for front single, rear single, and rear tandem axle load respectively.

2) On uphill flexible pavements, the amount of increase in rear axle load due to axle load redistribution is equal to the decrease in the corresponding front axle load for both tractor and trailer units. The resulting increased damage to the uphill pavement caused by the rear axle is much higher than the decreased damage caused by the corresponding front axle.

3) On uphill pavements, the magnitude of increase and decrease in the rear and front axle load, respectively, depends on total weight of each of tractor and trailer unit, the magnitude of the uphill slope, and the ratio of the height of the center of gravity to the wheelbase of each of tractor and trailer unit.

4) The maximum increase in axle load due to axle load redistribution on uphill flexible pavements takes place in connection with the rear axle of the

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tractor unit, while the maximum decrease occurs in connection with the front axle of the tractor unit.

5) This study confirms the non-linear correlation (power relation) between the pull force between the tractor and the trailer units and the weight of trailer unit suggested by another researcher.

6) For the same total weight of full-trailer trucks on uphill flexible pavements, the damage caused by each of full-trailer truck type 1.2+2.2, 11.2+2.2 and 1.2+2.22 is much greater than that caused by each of truck type 1.22+2.2, 1.22+2.22, and 11.22+2.22. For 620 kN total weight of full-trailer truck, SN=4, H/B=1.0 and pt=2.5, the ratio of the truck equivalency factor on uphill slope of 12% to that on level road pavement (0% slope) is 196%, 229%, 194%, 157%, 131% and 134% for 1.2+2.2, 11.2+2.2, 1.2+2.22, 1.22+2.2, 1.22+2.22 and 11.22+2.22 full-trailer trucks respectively.

7) The destructive effect of full-trailer trucks on uphill flexible pavements is greater than on level pavements for all values of SN. This is especially true for type 1.2+2.2, 1.2+2.22 and 11.2+2.2full-trailer trucks. For full-trailer truck type 11.2+2.2 with a total weight of 620 kN, SN=4, H/B=1 and p_t=2.5, the ratio of the truck equivalency factor for 18% uphill slope to that for a level highway is 171.13/51.72 =331%.

8) The full-trailer truck equivalency factor on uphill flexible pavements increases significantly with increasing the magnitude of H/B ratio. For full-trailer truck type 1.2+2.2 with a total weight of 620 kN, SN=4, uphill slope of 12% and p_t=2.5, the ratio of the truck equivalency factor for H/B =1 to that for H/B=0.2 is 165%.

9) The full-trailer truck equivalency factor on uphill flexible pavements generally decreases with increasing the structural number. For full- trailer truck type 1.2+2.2 with a total weight of 620 kN, H/B=1, uphill slope of 12% and p_t=2.5, the truck equivalency factor decreases from 302 for SN=1 to 141 for SN=6.

10) For each type of full-trailer truck, the truck equivalency factor decreases with increasing the terminal level of serviceability. For full-trailer truck type 11.2+2.2, SN=4, H/B=1 and uphill slope of 12%,the ratio of the truck equivalence factor for p_t=2 to that for p_t=3 is 231%.

11) The increase in the destructive effect of the full-trailer truck on an uphill flexible pavement is quite significant for full-trailer trucks type 1.2+2.2, 1.2+2.22 and 11.2+2.2 having total weights exceeding 400 kN. For full-trailer trucks type 1.22+2.2, 1.22+2.22 and 11.22+2.22, this phenomenon becomes obvious for total weights exceeding 500 kN.

12) On uphill pavements, the thickness of flexible pavement structure increases significantly with increasing the uphill gradient. This increase is more pronounced in the cases of 1.2+2.2, 1.2+2.22 and 11.2+2 than in the cases of 1.22+2.2, 1.22+2.22 and 11.22+2.22 full-trailer trucks. For full- trailer truck type 1.2+2.2 with a total weight of 450 kN, H/B=1, SN of pavement=4, and p_t=2, the base layer thickness increased about 2.93in (74.42mm)when increasing the uphill slope from 0 to 12%.

13) For each full-trailer truck type, the average truck equivalency factor increases with increasing the magnitude of uphill slope and H/B ratio for the same structural number and terminal level of serviceability.

6.2 Recommendations

1) To reduce the damage to uphill flexible pavements from overloaded full-trailer trucks, it is recommended to enforce the axle load limits on Iraqi rural highways.

2) It is recommended to update the Highway Design Manual of the State Commission of Roads and Bridges in Iraq for the new types of trucks that entered the service.

3) For the design of uphill flexible pavements, it is recommended to make use of the computer program and charts of full-trailer truck equivalency factors developed in this work.

4) It is recommended to encourage the use of tandem rear axles for tractor and trailer units of full-trailer trucks to decrease the damaging effect of full-trailer trucks on uphill pavements.

5) It is recommended to install portable weigh pads on Iraqi highways that are commonly used for axle load survey in many countries in the world.

6) For each type of trucks, it is recommended to make use of the average truck equivalency factor based on averaging the truck equivalency factors of all trucks of the same type. This average truck equivalency factor is more conservative than that based on the average total weight of the full-trailer trucks of the same type.

6.3 Recommendations for Future Research

1) It is recommended to extend this work to the case of semi-trailer trucks.

2) It is worth to extend the study of this work concerning the truck equivalency factors for full-trailer truck types 11.2+2.2 and 11.22+2.22 to uphill rigid pavements.

3) It will be interesting to study the effect of the inertia force on the damage of various trucks on uphill pavements and to develop design charts for each of flexible and rigid pavements.

4) It will be useful to extend this work to an economic study of the cost of increased pavement thickness on uphill pavements in both developed and developing countries.

5) It is recommended to examine the effect of pavement condition (e.g. wet pavement) on the pull force between tractor and trailer units of full-trailer trucks.

6) It is recommended to study the stress and strain (mechanistic methods) on the uphill flexible pavement from full-trailer truck.

7) It is recommended to determine the sample size of data by using more accurate equation, that is $(z\ \sigma/E)^2$.

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A

APPENDIX A

RESULTS OF AXLE LOAD SURVEY OF THIS STUDY FOR FULL-TRAILER TRUCKS TYPE 11.2+2.2 and 11.22+2.22

APPENDIX A

RESULTS OF AXLE LOAD SURVEY OF THIS STUDY FOR FULL-TRAILER TRUCKS TYPE 11.2+2.2 and 11.22+2.22

Table (A.1) Axle load survey sheet for full-trailer trucks.

Axle load survey Sheet Number

Location of survey: ……………………………….. Date of survey: ………/……/…….

Axle configuration	L= loaded E= empty	Fo_1 (kg)	Ro_1 (kg)	Fo_2 (kg)	Ro_2 (kg)	W_1 (kg)	W_2 (kg)	W_{total} (kg)

L= loaded truck
E= empty truck
Fo_1 = front axle load of tractor, in tonne
Ro_1 = rear axle load of tractor, in tonne
Fo_2 = front axle load of trailer, in tonne
Ro_2 = rear axle load of trailer, in tonne
* 1 tonne = 1000 kg

W_{total} = total weight of full-trailer truck, in tonne
W_1 = total weight of tractor, in tonne
W_2 = total weight of trailer, in tonne
W_1' = W_1+ Fo_2, in tonne
Ro_1= W_1- Fo_1 , W_2= Wt- W_1 , Fo_2= W_1' - W_1

Tables A.2 through A.3 show the results of the axle loads for 11.2+2.2 and 11.22+2.22 full-trailers surveyed respectively.

Table (A.2) Axle load data of 11.2+2.2 full trailers surveyed *.

F_{O1} (kg)	R_{O1} (kg)	F_{O2} (kg)	R_{O2} (kg)	W_1 (kg)	W_2 (kg)
14500	16460	10324	16646	30960	26970
9880	5680	5410	6440	15560	11850
13016	13744	8226	14944	26760	23170
17000	19500	9900	15400	36500	25300
15290	19590	10268	19282	34880	29550
16200	18100	9500	13900	34300	23400
16720	21640	11430	17620	38360	29050
17746	24034	12333	21817	41780	34150
17900	20000	10200	15900	37900	26100
14394	14491	8319	11366	28885	19685
17917	24433	11877	22703	42350	34580
13993	13712	8023	10842	27705	18865
15277	16204	8968	12521	31481	21489
17350	19500	9800	15400	36850	25200
12900	11800	7230	10200	24700	17430
15698	17022	9278	13072	32720	22350
15898	17422	9278	13472	33320	22750
16440	18473	9677	14180	34913	23857
18430	25630	12935	20415	44060	33350
18772	26428	12565	24165	45200	36730
17314	18956	9729	15071	36270	24800
17633	19522	9938	15477	37155	25415
17930	20051	10133	15856	37981	25989
14976	18784	10786	20384	33760	31170
18334	20768	10398	16370	39102	26768
18119	20387	10257	16097	38506	26354
17512	23488	13306	23624	41000	36930
18460	25700	14068	23702	44160	37770
18695	21410	10635	16830	40105	27465
19799	23374	11360	18237	43173	29597
18865	21712	10747	17046	40577	27793

Table (A.2) Continued.

18495	21055	10504	16576	39550	27080
18688	21398	10630	16821	40086	27451
15682	20598	10620	20030	36280	30650
16869	23651	12783	24627	40520	37410
19650	23110	11262	18048	42760	29310
20033	23789	11513	18535	43822	30048
19226	22354	10984	17506	41580	28490
18601	26029	12428	23872	44630	36300
19799	23374	11360	18237	43173	29597
20075	23865	11541	18589	43940	30130
19955	24451	12251	18202	44406	30454
19890	25171	12420	18489	45061	30909
19532	20219	11558	15661	39751	27219
21680	23440	13050	17900	45120	30950
21987	23900	13263	18220	45887	31483

* F_{O1}, R_{O1} = Front and rear axle loads for tractor on a level surface.
F_{O2}, R_{O2} = Front and rear axle loads for trailer on a level surface.
W_1, W_2 = Total weights for the tractor and the trailer respectively.

Table (A.3) Axle load data of 11.22+2.22 full- trailers surveyed*.

F_{O1} (kg)	R_{O1} (kg)	F_{O2} (kg)	R_{O2} (kg)	W_1 (kg)	W_2 (kg)
9480	9841	5230	7890	17820	13120
16720	29170	12168	18662	41440	30830
14000	17936	7700	12700	29200	20400
16230	20874	8560	14800	33920	23360
9880	10337	5460	8170	18640	13630
16000	21122	8700	14500	33900	23200
17906	30461	11514	22066	43720	33580
12889	13831	6434	10286	24610	16720
19091	33434	12409	23966	47425	36375
14497	23049	9988	15252	34030	25240
13892	16128	7172	11598	27560	18770
14694	17966	7762	12648	29920	20410
15096	18885	8058	13172	31100	21230
15417	19620	8294	13592	32044	21886
15617	20080	8441	13855	32634	22296
15898	20723	8648	14222	33460	22870
14497	23049	9988	15252	34030	25240

Table (A.3) Continued.

16837	22874	9339	15450	36221	24789
17282	23894	9666	16033	37531	25699
17503	24399	9829	16321	38180	26150
18105	25778	10272	17108	39950	27380
15694	26345	11162	17088	38020	28250
16099	21183	8796	14484	34050	23280
17503	24399	9829	16321	38180	26150
17904	25318	10124	16846	39360	26970
18907	27616	10862	18158	42310	29020
19285	32598	14161	21340	46910	35500
18105	25778	10272	17108	39950	27380
19890	29867	11585	19444	45201	31029
18526	26743	10582	17659	41189	28241
16099	21183	8796	14484	34050	23280
15697	20264	8500	13960	32870	22460
19065	27979	10979	18365	42776	29344
13691	15669	7024	11336	26970	18360
20712	31751	12190	20520	47620	32710
15028	24511	10529	19971	35800	30500
17680	31813	13140	25520	44640	38660
13642	20695	9149	13941	31180	23090
20371	30970	11939	20074	46617	32013
17322	23986	9696	16085	37649	25781
20000	30120	11666	19588	45526	31255
15123	25378	10480	16830	36630	27310
17440	24308	9800	16300	38040	26100

* F_{O1}, R_{O1} = Front and rear axle loads for tractor on a level surface.
F_{O2}, R_{O2} = Front and rear axle loads for trailer on a level surface.
W_1, W_2 = Total weights for the tractor and the trailer respectively.

B

APPENDIX B

THE SURVEY RESULTS OF AXLE GEOMETRY AND VEHICLE DIMENSIONS OF FULL- TRAILER TRUCKS SURVEY OF THIS STUDY

APPENDIX B

THE SURVEY RESULTS OF AXLE GEOMETRY AND VEHICLE DIMENSIONS OF FULL- TRAILER TRUCKS SURVEY OF THIS STUDY

Table (B.1) Geometrical characteristics survey sheet for full-trailer trucks.

Geometrical Characteristics Survey Sheet Number [ ]

Location of Survey: ……………………………… **Date of Survey:** ………/……/…….

No. of truck in axle load survey	Axle configuration	S_{11} (mm)	S_{12} (mm)	S_{13} (mm)	B_1 (mm)	S_{21} (mm)	S_{22} (mm)	B_2 (mm)	H_1 (mm)	H_2 (mm)	H_3 (mm)	H_4 (mm)

S_{11}= Distance between two axles of the front tandem axle.
S_{12} = Clear distance between the front and rear axles of the tractor unit.
S_{13} = Distance between two axles of the rear tandem axle of the tractor.
S_{21} = Clear distance between the front and rear axles of the trailer unit.
S_{22} = Distance between two axles of the rear tandem axle of the trailer unit.
B_1, B_2 = Wheel base lengths for the tractor and the trailer units respectively.
H_1, H_3 = Heights from the road surface to the bottom of the truck basin for the tractor and trailer units respectively.
H_2, H_4 = Heights from the road surface to the top of the truck basin for the tractor and trailer units respectively.

Tables B.2 through B.3 show the results of the axle geometry and vehicle dimensions for 11.2+2.2 and 11.22+2.22 full-trailer trucks surveyed respectively.

Table (B.2) Geometrical characteristics of 11.2+2.2 full-trailer trucks surveyed *.

S_{11} (mm)	S_{12} (mm)	B_1 (mm)	B_2 (mm)	H_1 (mm)	H_2 (mm)	H_3 (mm)	H_4 (mm)
1700	3860	4710	5440	1276	2900	1256	3200
1760	4000	4880	5600	1280	2850	1265	3270
1730	3900	4765	5340	1300	3000	1532	3100
1690	3890	4735	5400	1234	2800	1592	3120
1660	4200	5030	5670	1239	2400	1329	2900
1780	4130	5020	5600	1420	3000	1300	3000
1820	3790	4700	5430	1296	2400	1420	3500
1700	3870	4720	5347	1320	2620	1341	2900
1680	4329	5169	5450	1345	2670	1523	2830
1670	3970	4805	5400	1298	2950	1533	2900
1800	2080	2980	4898	1326	2960	1256	3000
1760	2120	3000	5100	1350	2450	1429	2830
1650	1825	2650	4924	1300	2400	1399	2900
1740	2000	2870	4390	1340	2680	1470	2900
1770	3665	4550	4987	1298	2900	1539	3300
1800	3672	4572	3990	1340	2730	1320	2950
1870	1945	2880	4920	1320	3000	1499	3100
1900	3110	4060	4998	1299	2980	1300	2840
1760	3185	4065	4570	1280	2850	1265	3270
1830	3960	4875	5590	1298	2900	1539	3300
1770	4360	5245	5500	1340	3420	1320	2950
1690	4190	5035	5430	1320	3000	1499	3100
1700	3869	4719	5460	1299	2980	1300	2840
1820	3980	4890	5530	1309	2440	1420	3990
1750	3900	4775	5550	1430	3000	1310	2900
1760	3880	4760	5400	1430	2810	1400	3300
1840	3860	4780	5420	1340	2410	1300	3200
1760	4100	4980	5438	1390	2900	1542	2950
1880	4230	5170	5560	1400	2870	1255	2700
1830	4580	5495	5610	1398	2587	1423	2950
1750	4200	5075	5670	1234	2550	1299	2990
1700	3850	4700	5400	1300	2970	1532	2900
1690	3900	4745	5440	1367	2640	1478	2830
1760	3980	4860	5420	1395	3000	1632	2950
1850	3990	4915	5430	1300	2790	1243	2680
1820	4180	5090	5700	1300	2900	1532	2900
1730	4250	5115	5430	1367	2399	1530	2950
1920	2203	3163	3880	1345	2890	1600	3020
1670	1995	2830	3970	1293	2920	1299	2830
1740	3170	4040	4000	1299	2840	1359	3140
1790	2225	3120	4570	1328	3050	1387	3200
1900	3350	4300	4870	1395	2660	1532	2900

! **Table (B.2) Continued.**

1870	2255	3190	5000	1399	2880	1530	3200
1800	2267	3167	5100	1367	2640	1478	2830
1670	1870	2705	4340	1300	2600	1534	2800
1890	3879	4824	5590	1420	3130	1440	3880

* S_{11}= Distance between two axles of the front tandem axle of the tractor unit type (11.2).
S_{12} = Clear distance between the front and rear axles of the tractor unit type (11.2).
B_1, B_2 = Wheel base lengths for the tractor and the trailer units respectively.
H_1, H_3 = Heights from the road surface to the bottom of the truck basin for the tractor and trailer units respectively.
H_2, H_4 = Heights from the road surface to the top of the truck basin for the tractor and trailer units respectively.

Table (B.3) Geometrical characteristics of 11.22+2.22 full- trailer trucks surveyed*.

S_{11} (mm)	S_{12} (mm)	S_{13} (mm)	B_1 (mm)	S_{21} (mm)	S_{22} (mm)	B_2 (mm)	H_1 (mm)	H_2 (mm)	H_3 (mm)	H_4 (mm)
1680	2700	1360	4220	4300	1300	4950	1300	3200	1490	3480
1700	2450	1360	3980	4500	1390	5195	1400	2800	1710	3000
1630	2840	1310	4310	4520	1350	5195	1320	2784	1670	3340
1800	2800	1300	4350	4000	1360	4680	1440	2900	1600	3500
1845	1433	1290	3000	3550	1300	4200	1420	3000	1533	3280
1823	3629	1320	5200	3578	1245	4200	1300	2734	1600	2890
1822	1374	1250	2910	3361	1298	4010	1400	3000	1440	3100
1700	2426	1349	3950	4695	1390	5390	1410	3000	1300	2800
1745	3438	1279	4950	4080	1340	4750	1390	2999	1650	3560
1723	2037	1324	3560	4336	1328	5000	1340	3120	1654	3500
1860	2600	1340	4200	4300	1370	4985	1390	3000	1560	3450
1700	3000	1360	4530	4280	1380	4970	1380	2800	1400	2900
1620	2870	1290	4325	4600	1300	5250	1350	3100	1560	2935
1600	2900	1350	4375	4590	1320	5250	1400	3155	1620	2800
1740	2560	1360	4110	4300	1340	4970	1420	3000	1533	3280
1680	2800	1300	4290	4500	1360	5180	1300	2734	1600	3260
1770	2218	1270	3738	3320	1340	3990	1460	3700	1400	3690
1780	2500	1340	4060	4120	1350	4795	1420	2934	1600	3200
1653	1422	1324	2910	3709	1379	4398	1470	2839	1634	3490
1800	3393	1234	4910	3562	1276	4200	1356	3200	1389	3700
1810	3467	1256	5000	3921	1299	4570	1420	3000	1650	3890
1830	2760	1320	4335	4500	1410	5205	1356	2960	1449	3200
1800	2700	1300	4250	4279	1380	4969	1300	3000	1540	3100
1750	2880	1350	4430	4330	1320	4990	1390	3100	1623	3333
1760	2790	1400	4370	4170	1300	4820	1400	2890	1590	3100
1740	2750	1340	4290	4380	1350	5055	1356	3200	1389	3700
1760	2480	1330	4025	4550	1400	5250	1420	3000	1650	3500
1770	2540	1360	4105	4619	1340	5289	1300	3190	1600	3320

Table (B.3) Continued.

1800	2950	1370	4535	4580	1330	5245	1347	3250	1580	3000
1660	2580	1360	4090	4640	1360	5320	1470	2839	1634	3490
1770	2180	1360	3745	2570	1340	3240	1300	3200	1490	3480
1760	2215	1300	3745	3310	1300	3960	1400	2800	1710	3000
1680	2450	1320	3950	3331	1299	3980	1410	2680	1400	3500
1760	2860	1390	4435	4350	1434	5067	1350	3144	1600	3400
1750	2500	1400	4075	4460	1400	5160	1320	2923	1560	2800
1700	2379	1360	3909	4289	1380	4979	1450	3290	1550	2990
1780	2900	1350	4465	4440	1400	5140	1370	3213	1630	3450
1780	2600	1400	4190	4523	1358	5202	1390	2999	1650	3000
1660	3100	1360	4610	4500	1420	5210	1340	3120	1654	3500
1790	2400	1390	3990	4567	1446	5290	1369	2970	1555	2990
1760	2340	1380	3910	4600	1400	5300	1400	3180	1456	2900
1700	2426	1349	3950	4695	1390	5390	1410	3000	1300	2800
1745	3438	1279	4950	4080	1340	4750	1390	2999	1650	3560

* S_{11}= Distance between two axles of the front tandem axle of the tractor unit type (11.22).
S_{12} = Clear distance between the front and rear axles of the tractor unit type (11.22).
S_{13} = Distance between two axles of the rear tandem axle of the tractor unit type (11.22).
S_{21} = Clear distance between the front and rear axles of the trailer unit type (2.22).
S_{22} = Distance between two axles of the rear tandem axle of the trailer unit type (2.22).
B_1, B_2 = Wheel base lengths for the tractor and the trailer units respectively.
H_1, H_3 = Heights from the road surface to the bottom of the truck basin for the tractor and trailer units respectively.
H_2, H_4 = Heights from the road surface to the top of the truck basin for the tractor and trailer units respectively.

C

APPENDIX C

THE SURVEY RESULTS OF UPHILL SLOPE

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APPENDIX C

THE SURVEY RESULTS OF UPHILL SLOPE

Table (C.1) Form for recording uphill slope data.

Uphill slope survey Sheet number

Location of survey: ....
Road length: ....
Road width: ....
Type of uphill slope: ....

Date of survey: ..../....../.......

Level reading (m)	Horizontal distance (m)	Slope (%)

Note:

$$uphill\ \ slope = \frac{difference\ \ in\ \ elevation\ \ (m)}{length\ \ of\ \ interval\ \ (m)}$$

Table C.2 shows the results of the uphill slope survey on Kerbala – Ein Al Tamur road. Tables C.3 through C.7 show the results of the uphill slope survey in Kerbala city interchanges.

Table (C.2) Level readings for uphill slope of Karbala -Ein Al –Tamuer road.

level reading (m)	Horizontal distance (m)	Slope (%)
3.230	0.00	6.20
2.920	5.00	6.20
2.610	10.00	6.40
2.290	15.00	6.60
1.960	20.00	6.60
1.630	25.00	6.80
4.500* 1.300	30.00	7.00
4.160*	35.00	7.00
3.810*	40.00	7.00
3.459*	45.00	7.00
3.109*	50.00	6.84
2.759*	55.00	6.82
2.417*	60.00	6.40
2.076* 3.070**	65.00	6.40
**2.750	70.00	6.20
**2.430	75.00	6.00
**2.120	80.00	
**1.820	85.00	

* 1st turning point ** 2nd turning point

Table (C.3) Level readings for uphill slope of Imam Ali -interchange (Ramp no.1).

level reading (elevation) (m)	Horizontal distance (m)	Slope (%)
3.320	0.00	4.46
3.097	5.00	4.62
2.866	10.00	5.00
2.616	15.00	5.00
2.366	20.00	4.84
2.124	25.00	

Table (C.4) Level readings for uphill slope of Imam Ali –interchange's Approach.

level reading (elevation) (m)	Horizontal distance (m)	Slope (%)
2.578	0.00	
2.380	5.00	3.96
2.180	10.00	4.00
1.980	15.00	4.00
1.779	20.00	4.00
1.580	25.00	3.98

Table (C.5) Level readings for uphill slope of Imam Ali -interchange (Ramp no.3)

level reading (elevation) (m)	Horizontal distance (m)	Slope (%)
3.674	0.00	
3.435	5.00	4.78
3.185	10.00	5.00
2.935	15.00	5.00
2.684	20.00	5.00
2.440	25.00	4.88

Table (C.6) Level readings for uphill slope of Al- Malab interchange's Approach.

level reading (elevation) (m)	Horizontal distance (m)	Slope (%)
2.890	0.00	
2.651	5.00	4.78
2.401	10.00	5.00
2.151	15.00	5.00
1.906	20.00	4.90
1.668	25.00	4.76

Table (C.7) Level readings for uphill slope of Fatima Al-Zahraa interchange's Approach.

level reading (elevation) (m)	Horizontal distance (m)	Slope (%)
3.512	0.00	
3.290	5.00	4.44
3.066	10.00	4.48
2.841	15.00	4.50
2.616	20.00	4.50
2.392	25.00	4.48

D

APPENDIX D

TESTING OF NORMALITY OF AXLE LOAD DISTRIBUTION USING THE CHI-SQUARE GOODNESS OF FIT TEST

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APPENDIX D

TESTING OF NORMALITY OF AXLE LOAD DISTRIBUTION USING THE CHI-SQUARE GOODNESS OF FIT TEST

Since the type of distribution of the collected data influences the required sample size for any survey (Bluman, 2001), it is necessary to test the normality of axle load distribution for the collected data during the survey of this work.

For testing the normality, the chi-square (χ^2) goodness of fit test is to be used. Following (Bluman, 2001), the chi-square for grouped data can be calculated by the following formula:

$$\chi^2 = \sum_{i=1}^{g} \frac{(f_i - F_i)^2}{F_i} \qquad \textbf{(D.1)}$$

where:

f_i = observed frequency of the i^th^ interval.

F_i = expected absolute frequency of the i^th^ interval calculated using the following equation (D.2).

$$F(x) = \frac{N \times C}{s \times \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\bar{x}}{s}\right)^2} \qquad \textbf{(D.2)}$$

where:

C= length of class interval used to draw the histogram.

s = standard deviation of the sample, for grouped data, the standard deviation of the sample is given by (Bluman, 2001):

$$s = \pm\sqrt{\frac{1}{N-1} \times \sum_{i=1}^{g} \left(x_i - \bar{x}\right)^2 \times f_i} \qquad \textbf{(D.3)}$$

$\bar{x}$ = sample mean or arithmetic mean (average axle load) calculated using the following equation (D.4).

$$\bar{x} = \frac{\sum_{i=1}^{g} f_i \; x_i}{N} \qquad \textbf{(D.4)}$$

x_i = class mark of the ith axle load class.

f_i = number of observation in the ith class (absolute frequency).

g = number of classes (groups).

N= total number of observations.

The following method of testing the hypothesis of normality for the axle load distribution is based on the use of a simple spreadsheet program using automatic calculation in software Excel (2014)(see Figure (D.1)).

Tables (D.1, D.2, D.3, and D.4) show the details of this test for the cases of the front, rear axle load of the tractor unit and the front and rear axle load of the trailer unit respectively of full-trailer trucks type (11.22+2.22).

The critical chi-square (χ^2) was taken at a level of significance (α) of (5%) for a degree of freedom (DF=g-3) where (g= number of classes after regrouping).Note that there are two ways to regroup frequency, the first one makes regrouping for the absolute frequency (Kreyszig, 2006) and the second way makes regrouping for the expected frequency (Neville and Kennedy, 1964; Bluman, 2001). Adopted regrouping in this work followed the expected frequencies less than 5 (Bluman, 2001).

The calculations presented in Tables (D.1 to D.4) show that the frequency distribution for the different axle loads for both the tractor and the trailer units for case of type (11.22+2.22) full-trailer truck followed the normal distribution since the calculated (χ^2) for each distribution was less than the critical chi-square (χ^2_c) at a significance level (α) of (5%).

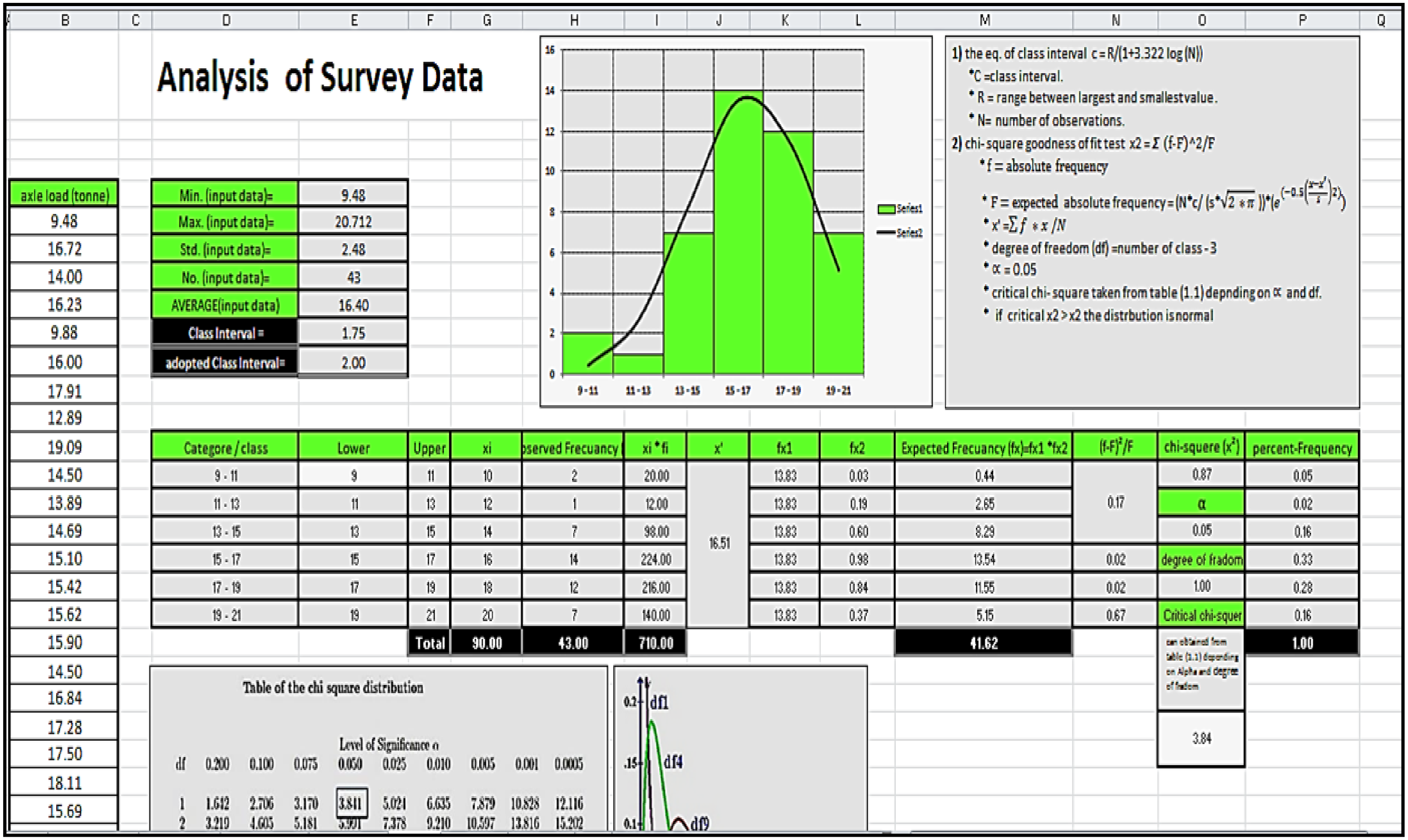

Fig. (D.1) Analysis of survey data for front tandem axle load of tractor unit type (11.22).

Table (D.1) Testing the normality of frequency distribution of the front axle loads for the tractor unit of full-trailer truck type (11.22+2.22).

Axle load class (tonne)	Class mark (tonne)	Observed frequency (fi)		Expected frequency (Fi)		$\frac{(f_i - F_i)^2}{F_i}$
9 - 11	10	2	10	0.48	11.14	0.17
11 - 13	12	1		2.68		
13 - 15	14	7		7.98		
15 - 17	16	14		13.54		0.02
17 - 19	18	12		11.55		0.02
19 - 21	20	7		5.15		0.67
	Total	43		χ^2		0.87

Average front axle load = 16.40 tonne

Standard deviation = 2.48 tonne

Number of classes after regrouping =4

Degree of freedom (DF) =1

Critical chi-square (χ^2_c) =3.841

χ^2_c > calculated χ^2 The distribution is normal

Table (D.2) Testing the normality of frequency distribution of the rear axle loads for the tractor unit of full-trailer truck type (11.22+2.22).

Axle load class (tonne)	Class mark (tonne)	Observed frequency (fi)		Expected frequency (Fi)		$\frac{(f_i - F_i)^2}{F_i}$
9- 13	11	2	5	1.03	4.89	0.00
13- 17	15	3		3.86		
17- 21	19	9		8.77		0.06
21- 25	23	12		12.07		0.00
25- 29	27	8		10.08		0.14
29- 33	31	8	9	5.11	6.68	0.81
33- 37	35	1		1.57		
	Total	43		χ^2		1.25

Average front axle load = 23.53 tonne

Standard deviation = 5.66 tonne

Number of classes after regrouping =5

Degree of freedom (DF) =2

Critical chi-square (χ^2_c) =5.991

χ^2_c > calculated χ^2 The distribution is normal

Table (D.3) Testing the normality of frequency distribution of the front axle loads for the trailer unit of full-trailer truck type (11.22+2.22).

Axle load class (tonne)	Class mark (tonne)	Observed frequency (fi)		Expected frequency (Fi)		$\frac{(f_i - F_i)^2}{F_i}$
5 - 6.5	5.75	3	7	1.63	7.51	0.03
6.5 - 8	7.25	4		5.88		
8 - 9.5	8.75	11		11.68		0.04
9.5 - 11	10.25	15		12.78		0.39
11 - 12.5	11.75	8	10	7.70	10.73	0.05
12.5 - 14	13.25	1		2.56		
14 - 15.5	14.75	1		0.47		
	Total	43		χ^2		0.51
Average front axle load = 9.70 tonne						
Standard deviation = 1.94 tonne						
Number of classes after regrouping =4						
Degree of freedom (DF) =1						
Critical chi-square (χ^2_c) =3.841						
χ^2_c > calculated χ^2	The distribution is normal					

Table (D.4) Testing the normality of frequency distribution of the rear axle loads for the trailer unit of full-trailer truck type (11.22+2.22).

Axle load class (tonne)	Class mark (tonne)	Observed frequency (fi)		Expected frequency (Fi)		$\frac{(f_i - F_i)^2}{F_i}$
7 - 10	8.5	2	7	1.48	9.24	0.02
10 - 13	11.5	5		5.86		
13 - 16	14.5	13		12.15		0.06
16 - 19	17.5	14		13.20		0.05
19 - 22	20.5	6	9	7.51	8.00	0.12
22 - 25	23.5	2		2.24		
25 - 28	26.5	1		0.35		
	Total	43		χ^2		0.24
Average front axle load = 16.12 tonne						
Standard deviation = 3.73 tonne						
Number of classes after regrouping =4						
Degree of freedom (DF) =1						
Critical chi-square (χ^2_c) =3.841						
χ^2_c > calculated χ^2	The distribution is normal					

E

APPENDIX E

COMPUTER PROGRAMS

APPENDIX E

COMPUTER PROGRAMS

The program FEFUF (Full-trailer Equivalence Factor for Uphill Flexible pavements) was written in MATLAB as follows:

```
 *************************************************************************************
* Name of program : Full-trailer Equivalence Factor for Uphill Flexible pavement(FEFUF)   *
* Written in      : MATLAB PROGRAM (2008)                                               *
* Developed by    : Eng. ZAHRAA H. MASH'A ALLAH                                         *
* B.Sc.           : CIVIL ENGINEERING                                                   *
* Place of Study  : IRAQ UNIVERSITY of KERBALA                                          *
* Yahoo. Mail     : zahraa_hashim1992@yahoo.com                                         *
 *************************************************************************************
```

Clear everything from command windows.

```
clear all; close all; clc;
```

Input all constant data.

```
n1=input ('enter number of the full-trailers of type 1.2+2.2=');
n2=input ('enter number of the full-trailers of type 1.2+2.22=');
n3=input ('enter number of the full-trailers of type 1.22+2.2=');
n4=input ('enter number of the full-trailers of type 1.22+2.22=');
n5=input ('enter number of the full-trailers of type 11.2+2.2=');
n6=input ('enter number of the full-trailers of type 11.22+2.22=');
k=input  ('enter type of the full-trailers=');
% k=1 (full trailers of type 1.2+2.2).
% k=2 (full trailers of type 1.2+2.22).
% k=3 (full trailers of type 1.22+2.2).
% k=4 (full trailers of type 1.22+2.22).
% k=5 (full trailers of type 11.2+2.2).
% k=6 (full trailers of type 11.22+2.22).
HB=input ('enter ratio of height of center of gravity to the wheel base of the full-trailer
truck=');
Q=input ('enter gradient=');
% Q = magnitude of uphill slope (%) divided by 100.
SN= input ('enter structural number=');
N = input ('enter total number of the full trailers=');
pt= input ('enter the terminal level of serviceability=');
E= 1000;
% E= height of the pull force above the pavement in mm.
Q= atan (Q);
zzz= cos(Q);
factor1=102.02317;
% factor1 to convert the unit of axle load from (kg) to (kN).
factor2=4.4482216172;
% factor2 to convert the unit of axle load from (kN) to (kips).
```

Determine the truck equivalence factor for full trailer on uphill slope (Teg).

```
if k==1
    for i=1:n1
```

```
data = xlsread('1.2+2.2.xlsx',1);
Fo1(i)= data(i,1);
% Fo1= front axle load for the tractor unit on level road in kg.
Ro1(i)= data(i,2);
% Ro1= rear axle load for the tractor unit on level road in kg.
Fo2(i)= data(i,3);
% Fo2= front axle load for the trailer unit on level road in kg.
Ro2(i)= data(i,4);
% Ro2= rear axle load for the trailer unit on level road in kg.
B1(i)= data(i,7);
% B1= wheelbase length for tractor in mm.
B2(i)= data(i,8);
% B2= wheelbase length for trailer in mm.
Fo1(i)= Fo1(i)./factor1;
Ro1(i)= Ro1(i)./factor1;
Fo2(i)= Fo2(i)./factor1;
Ro2(i)= Ro2(i)./factor1;
Wo1(i)= Fo1(i)+Ro1(i);
% Wo1=total weight of tractor of type 1.2+2.2 in kN.
Wo2(i)=Fo2(i)+Ro2(i);
%Wo2=total weight of trailer of type 1.2+2.2 in kN.
Wot(i)=Wo1(i)+Wo2(i);
% Wot= total weight of truck 1.2+2.2 in KN.
To(i)=0.0008.*(Wo2(i).*zzz)^1.5433;
% To = pull force between tractor and trailer for full trailer type 1.2+2.2 on level
    highway in kN.
T(i)=To(i)+Wo2(i)*sin(Q);
% T = pull force between tractor and trailer for full trailer type 1.2+2.2 on uphill
    slope in kN.
FG1(i) = Fo1(i)*zzz-Wo1(i).*(sin(Q)*HB)-T(i).*(E./B1(i));
% FG1= front axle load of tractor on upgrade in kN.
RG1(i) = Ro1(i)*zzz+Wo1(i).*(sin(Q)*HB)+T(i).*(E./B1(i));
% RG1= rear axle load of tractor on upgrade in kN.
FG2(i) = Fo2(i)*zzz-Wo2(i).*(sin(Q)*HB)+T(i).*(E./B2(i));
% FG1= front axle load of trailer on upgrade in kN.
RG2(i) = Ro2(i)*zzz+Wo2(i).*(sin(Q)*HB)-T(i).*(E./B2(i));
% RG2= rear axle load of trailer on upgrade in kN.
A= (4.2-pt)/2.7;
Gt= log10(A);
X18 = (0.4+((0.081*(18+1)^3.23)/((SN+1)^5.19*(1)^3.23)));
% Xg = the shape function
% X18=value of Xg when load of axle is standard axle load (18 kips=80 kN) and axle
   code=1
FG1(i)=FG1(i)./factor2;
RG1(i)=RG1(i)./factor2;
FG2(i)=FG2(i)./factor2;
RG2(i)=RG2(i)./factor2;
ag1(i) =( FG1(i) +1)^3.23;
ag2(i) =( RG1(i) +1)^3.23;
ag3(i) =( FG2(i) +1)^3.23;
ag4(i) =( RG2(i) +1)^3.23;
Xg1(i) =(0.4+((0.081*ag1(i) )/((SN+1)^5.19*(1)^3.23)));
Xg2(i) =(0.4+((0.081*ag2(i) )/((SN+1)^5.19*(1)^3.23)));
Xg3(i) =(0.4+((0.081*ag3(i) )/((SN+1)^5.19*(1)^3.23)));
Xg4(i) =(0.4+((0.081*ag4(i) )/((SN+1)^5.19*(1)^3.23)));
Eig1 (i)=((FG1(i) +1)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg1(i) )*(1^4.33)));
```

```
    % Eig1=AASHTO load equivalency factor for the front axle of tractor on uphill slope.
    Eig2(i) =(( RG1(i) +1)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg2(i))*(1^4.33)));
    % Eig2=AASHTO load equivalency factor for the rear axle of tractor on uphill slope.
    Eig3 (i)=(( FG2(i) +1)^4.79 /(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg3(i) )*(1^4.33)));
    % Eig3=AASHTO load equivalency factor for the front axle of trailer on uphill slope.
    Eig4(i) =(( RG2(i) +1)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg4(i))*(1^4.33)));
    % Eig4=AASHTO load equivalency factor for the rear axle of trailer on uphill slope.
    Teg (i)= Eig1(i) +Eig2(i)+Eig3(i)+Eig4(i);
    % Teg=truck equivalence factor for full trailer on uphill slope.
end
Te=sum (Teg);
Ta=Te/n1;
% Ta=average truck equivalence factor.
elseif k==2
for i=1:n2
    data1=xlsread ('1.2+2.22.xlsx',1);
    Fo1(i)=data1(i,1);
    Ro1(i)=data1(i,2);
    Fo2(i)=data1(i,3);
    Ro2(i)=data1(i,4);
    B1(i)=data1(i,7);
    B2(i)=data1(i,8);
    Fo1(i)=Fo1(i)./factor1;
    Ro1(i)=Ro1(i)./factor1;
    Fo2(i)=Fo2(i)./factor1;
    Ro2(i)=Ro2(i)./factor1;
    Wo1(i)=Fo1(i)+Ro1(i);
    Wo2(i)=Fo2(i)+Ro2(i);
    Wot(i)=Wo1(i)+ Wo2(i);
    To(i)=0.0008.*(Wo2(i).*zzz)^1.5433;
    T(i)=To(i)+Wo2(i)*sin(Q);
    FG1(i) = Fo1(i)*zzz-Wo1(i).*(sin(Q)*HB)-T(i).*(E./B1(i));
    RG1(i) = Ro1(i)*zzz+Wo1(i).*(sin(Q)*HB)+T(i).*(E./B1(i));
    FG2(i) = Fo2(i)*zzz-Wo2(i).*(sin(Q)*HB)+T(i).*(E./B2(i));
    RG2(i) = Ro2(i)*zzz+Wo2(i).*(sin(Q)*HB)-T(i).*(E./B2(i));
    A=(4.2-pt)/2.7;
    Gt=log10(A);
    X18 =(0.4+((0.081*(18+1)^3.23)/((SN+1)^5.19*(1)^3.23)));
    FG1(i)=FG1(i)./factor2;
    RG1(i)=RG1(i)./factor2;
    FG2(i)=FG2(i)./factor2;
    RG2(i)=RG2(i)./factor2;
    ag1(i) =( FG1(i) +1)^3.23;
    ag2(i) =( RG1(i) +1)^3.23;
    ag3(i) =( FG2(i) +1)^3.23;
    ag4(i) =( RG2(i) +2)^3.23;
    Xg1(i) =(0.4+((0.081*ag1(i) )/((SN+1)^5.19*(1)^3.23)));
    Xg2(i) =(0.4+((0.081*ag2(i) )/((SN+1)^5.19*(1)^3.23)));
    Xg3(i) =(0.4+((0.081*ag3(i) )/((SN+1)^5.19*(1)^3.23)));
    Xg4(i) =(0.4+((0.081*ag4(i) )/((SN+1)^5.19*(2)^3.23)));
    Eig1 (i)=((FG1(i) +1)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg1(i))*(1^4.33)));
    Eig2(i) =(( RG1(i) +1)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg2(i))*(1^4.33)));
    Eig3 (i)=(( FG2(i) +1)^4.79 /(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg3(i))*(1^4.33)));
    Eig4(i) =(( RG2(i) +2)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg4(i))*(2^4.33)));
    Teg (i)= Eig1(i) +Eig2(i)+Eig3(i)+Eig4(i);
end
```

```
    Te=sum(Teg);
    Ta=Te/n2;
    elseif k==3
    for i=1:n3
       data2=xlsread('1.22+2.2.xlsx',3);
       Fo1(i)=data2(i,1);
       Ro1(i)=data2(i,2);
       Fo2(i)=data2(i,3);
       Ro2(i)=data2(i,4);
       B1(i)=data2(i,5);
       B2(i)=data2(i,6);
       Fo1(i)=Fo1(i)./factor1;
       Ro1(i)=Ro1(i)./factor1;
       Fo2(i)=Fo2(i)./factor1;
       Ro2(i)=Ro2(i)./factor1;
       Wo1(i)=Fo1(i)+Ro1(i);
       Wo2(i)=Fo2(i)+Ro2(i);
       Wot(i)=Wo1(i)+ Wo2(i);
       To(i)=0.0008.*(Wo2(i).*zzz)^1.5433;
       T(i)=To(i)+Wo2(i)*sin(Q);
       FG1(i) = Fo1(i)*zzz-Wo1(i).*(sin(Q)*HB)-T(i).*(E./B1(i));
       RG1(i) = Ro1(i)*zzz+Wo1(i).*(sin(Q)*HB)+T(i).*(E./B1(i));
       FG2(i) = Fo2(i)*zzz-Wo2(i).*(sin(Q)*HB)+T(i).*(E./B2(i));
       RG2(i) = Ro2(i)*zzz+Wo2(i).*(sin(Q)*HB)-T(i).*(E./B2(i));
       A=(4.2-pt)/2.7;
       Gt=log10(A);
       X18 =(0.4+((0.081*(18+1)^3.23)/((SN+1)^5.19*(1)^3.23)));
       FG1(i)=FG1(i)./factor2;
       RG1(i)=RG1(i)./factor2;
       FG2(i)=FG2(i)./factor2;
       RG2(i)=RG2(i)./factor2;
       ag1(i) =( FG1(i) +1)^3.23;
       ag2(i) =( RG1(i) +2)^3.23;
       ag3(i) =( FG2(i) +1)^3.23;
       ag4(i) =( RG2(i) +1)^3.23;
       Xg1(i) =(0.4+((0.081*ag1(i) )/((SN+1)^5.19*(1)^3.23)));
       Xg2(i) =(0.4+((0.081*ag2(i) )/((SN+1)^5.19*(2)^3.23)));
       Xg3(i) =(0.4+((0.081*ag3(i) )/((SN+1)^5.19*(1)^3.23)));
       Xg4(i) =(0.4+((0.081*ag4(i) )/((SN+1)^5.19*(1)^3.23)));
       Eig1 (i)=((FG1(i) +1)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg1(i))*(1^4.33)));
       Eig2(i) =((RG1(i) +2)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg2(i))*(2^4.33)));
       Eig3 (i)=((FG2(i) +1)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg3(i))*(1^4.33)));
       Eig4(i) =((RG2(i) +1)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg4(i))*(1^4.33)));
       Teg (i)= Eig1(i) +Eig2(i)+Eig3(i)+Eig4(i);
    end
    Te=sum(Teg);
    Ta=Te/n3;
    elseif k==4
    for i=1:n4
       data3=xlsread('1.22+2.22.xlsx',3);
       Fo1(i)=data3(i,1);
       Ro1(i)=data3(i,2);
       Fo2(i)=data3(i,3);
       Ro2(i)=data3(i,4);
       B1(i)=data3(i,5);
       B2(i)=data3(i,6);
```

```
      Fo1(i)=Fo1(i)./factor1;
      Ro1(i)=Ro1(i)./factor1;
      Fo2(i)=Fo2(i)./factor1;
      Ro2(i)=Ro2(i)./factor1;
      Wo1(i)=Fo1(i)+Ro1(i);
      Wo2(i)=Fo2(i)+Ro2(i);
      Wot(i)=Wo1(i)+ Wo2(i);
      To(i)=0.0008.*(Wo2(i).*zzz)^1.5433;
      T(i)=To(i)+Wo2(i)*sin(Q);
      FG1(i)  = Fo1(i)*zzz-Wo1(i).*(sin(Q)*HB)-T(i).*(E./B1(i));
      RG1(i)  = Ro1(i)*zzz+Wo1(i).*(sin(Q)*HB)+T(i).*(E./B1(i));
      FG2(i)  = Fo2(i)*zzz-Wo2(i).*(sin(Q)*HB)+T(i).*(E./B2(i));
      RG2(i)  = Ro2(i)*zzz+Wo2(i).*(sin(Q)*HB)-T(i).*(E./B2(i));
      A=(4.2-pt)/2.7;
      Gt=log10(A);
      X18 =(0.4+((0.081*(18+1)^3.23)/((SN+1)^5.19*(1)^3.23)));
      FG1(i)=FG1(i)./factor2;
      RG1(i)=RG1(i)./factor2;
      FG2(i)=FG2(i)./factor2;
      RG2(i)=RG2(i)./factor2;
      ag1(i)=( FG1(i) +1)^3.23;
      ag2(i)=( RG1(i) +2)^3.23;
      ag3(i)=( FG2(i) +1)^3.23;
      ag4(i)=( RG2(i) +2)^3.23;
      Xg1(i)=(0.4+((0.081*ag1(i))/((SN+1)^5.19*(1)^3.23)));
      Xg2(i)=(0.4+((0.081*ag2(i))/((SN+1)^5.19*(2)^3.23)));
      Xg3(i)=(0.4+((0.081*ag3(i))/((SN+1)^5.19*(1)^3.23)));
      Xg4(i)=(0.4+((0.081*ag4(i))/((SN+1)^5.19*(2)^3.23)));
      Eig1(i)=((FG1(i)+1)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg1(i))*(1^4.33)));
      Eig2(i)=((RG1(i)+2)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg2(i))*(2^4.33)));
      Eig3(i)=((FG2(i)+1)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg3(i))*(1^4.33)));
      Eig4(i)=((RG2(i)+2)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg4(i))*(2^4.33)));
      Teg (i)= Eig1(i) +Eig2(i)+Eig3(i)+Eig4(i);
   end
    Te=sum(Teg);
    Ta=Te/n4 ;
    elseif k==5
    for i=1:n5
      data4=xlsread('(11.2+2.2).xlsx',5);
      Fo1(i)=data4(i,1);
      Ro1(i)=data4(i,2);
      Fo2(i)=data4(i,3);
      Ro2(i)=data4(i,4);
      B1(i)=data4(i,5);
      B2(i)=data4(i,6);
      Fo1(i)=Fo1(i)./factor1;
      Ro1(i)=Ro1(i)./factor1;
      Fo2(i)=Fo2(i)./factor1;
      Ro2(i)=Ro2(i)./factor1;
      Wo1(i)=Fo1(i)+Ro1(i);
      Wo2(i)=Fo2(i)+Ro2(i);
      Wot(i)=Wo1(i)+ Wo2(i);
      To(i)=0.0008.*(Wo2(i).*zzz)^1.5433;
      T(i)=To(i)+Wo2(i)*sin(Q);
      FG1(i)  = Fo1(i)*zzz-Wo1(i).*(sin(Q)*HB)-T(i).*(E./B1(i));
      RG1(i)  = Ro1(i)*zzz+Wo1(i).*(sin(Q)*HB)+T(i).*(E./B1(i));
```

```
        FG2(i) = Fo2(i)*zzz-Wo2(i).*(sin(Q)*HB)+T(i).*(E./B2(i));
        RG2(i) = Ro2(i)*zzz+Wo2(i).*(sin(Q)*HB)-T(i).*(E./B2(i));
        A=(4.2-pt)/2.7;
        Gt=log10(A);
        X18 =(0.4+((0.081*(18+1)^3.23)/((SN+1)^5.19*(1)^3.23)));
        FG1(i)=FG1(i)./factor2;
        RG1(i)=RG1(i)./factor2;
        FG2(i)=FG2(i)./factor2;
        RG2(i)=RG2(i)./factor2;
        ag1(i)=( FG1(i) +2)^3.23;
        ag2(i)=( RG1(i) +1)^3.23;
        ag3(i)=( FG2(i) +1)^3.23;
        ag4(i)=( RG2(i) +1)^3.23;
        Xg1(i)=(0.4+((0.081*ag1(i))/((SN+1)^5.19*(2)^3.23)));
        Xg2(i)=(0.4+((0.081*ag2(i))/((SN+1)^5.19*(1)^3.23)));
        Xg3(i)=(0.4+((0.081*ag3(i))/((SN+1)^5.19*(1)^3.23)));
        Xg4(i)=(0.4+((0.081*ag4(i))/((SN+1)^5.19*(1)^3.23)));
        Eig1(i)=((FG1(i)+2)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg1(i))*(2^4.33)));
        Eig2(i)=((RG1(i)+1)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg2(i))*(1^4.33)));
        Eig3(i)=((FG2(i)+1)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg3(i))*(1^4.33)));
        Eig4(i)=((RG2(i)+1)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg4(i))*(1^4.33)));
        Teg (i)= Eig1(i) +Eig2(i)+Eig3(i)+Eig4(i);
    end
     Te=sum(Teg);
     Ta=Te/n5 ;
else
    for i=1:n6
        data5=xlsread('(11.22+2.22).xlsx',1);
        Fo1(i)=data5(i,1);
        Ro1(i)=data5(i,2);
        Fo2(i)=data5(i,3);
        Ro2(i)=data5(i,4);
        B1(i)=data5(i,5);
        B2(i)=data5(i,6);
        Fo1(i)=Fo1(i)./factor1;
        Ro1(i)=Ro1(i)./factor1;
        Fo2(i)=Fo2(i)./factor1;
        Ro2(i)=Ro2(i)./factor1;
        Wo1(i)=Fo1(i)+Ro1(i);
        Wo2(i)=Fo2(i)+Ro2(i);
        Wot(i)=Wo1(i)+ Wo2(i);
        To(i)=0.0008.*(Wo2(i).*zzz)^1.5433;
        T(i)=To(i)+Wo2(i)*sin(Q);
        FG1(i) = (Fo1(i)*zzz)-(Wo1(i).*(sin(Q).*HB))-(T(i).*(E./B1(i)));
        RG1(i) = (Ro1(i)*zzz)+(Wo1(i).*(sin(Q).*HB))+(T(i).*(E./B1(i)));
        FG2(i) = (Fo2(i)*zzz)-(Wo2(i).*(sin(Q).*HB))+(T(i).*(E./B2(i)));
        RG2(i) = (Ro2(i)*zzz)+(Wo2(i).*(sin(Q).*HB))-(T(i).*(E./B2(i)));
        A=(4.2-pt)/2.7;
        Gt=log10(A);
        X18 =(0.4+((0.081*(18+1)^3.23)/((SN+1)^5.19*(1)^3.23)));
        FG1(i)=FG1(i)./factor2;
        RG1(i)=RG1(i)./factor2;
        FG2(i)=FG2(i)./factor2;
        RG2(i)=RG2(i)./factor2;
        ag1(i)=( FG1(i) +2)^3.23;
        ag2(i)=( RG1(i) +2)^3.23;
```

```
        ag3(i)=( FG2(i) +1)^3.23;
        ag4(i)=( RG2(i) +2)^3.23;
        Xg1(i)=(0.4+((0.081*ag1(i))/((SN+1)^5.19*(2)^3.23)));
        Xg2(i)=(0.4+((0.081*ag2(i))/((SN+1)^5.19*(2)^3.23)));
        Xg3(i)=(0.4+((0.081*ag3(i))/((SN+1)^5.19*(1)^3.23)));
        Xg4(i)=(0.4+((0.081*ag4(i))/((SN+1)^5.19*(2)^3.23)));
        Eig1(i)=((FG1(i)+2)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg1(i))*(2^4.33)));
        Eig2(i)=((RG1(i)+2)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg2(i))*(2^4.33)));
        Eig3(i)=((FG2(i)+1)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg3(i))*(1^4.33)));
        Eig4(i)=((RG2(i)+2)^4.79/(18+1)^4.79)*(10^(Gt/X18)/(10^(Gt/Xg4(i))*(2^4.33)));
        Teg (i)= Eig1(i) +Eig2(i)+Eig3(i)+Eig4(i);
     end
      Te=sum(Teg);
      Ta=Te/n6;
end
```

Output of the program

```
table1 =[ Fo1' Ro1' Fo2' Ro2' T' FG1' RG1' FG2' RG2'];
% table1=[Fo1' Ro1' Fo2' Ro2' T' FG1' RG1' FG2' RG2];
disp(table1)
table2 =[Eig1' Eig2' Eig3' Eig4' Teg'];
% table2 =[Eig1' Eig2' Eig3' Eig4' Teg'];
disp(table2)
```

Output of the program in excel sheet

```
output= xlswrite('C:\Users\ALAHAD ALJADED\Desktop\output.xls',table2,1,'B2');
```

The (DTCFUF) program used to represent the output of FEFUF program as a chart and written in MATLAB as follows:

```
*******************************************************************************************
* Name of program : Drawing Truck equivalency factor Charts for Full-trailer trucks on   *
*                   Uphill Flexible pavements (DTCFUF)                                    *
* Written in      : MATLAB PROGRAM (2008)                                                 *
* Developed by    : Eng. ZAHRAA H. MASH'A ALLAH                                           *
* B.Sc.           : CIVIL ENGINEERING                                                     *
* Place of Study  : IRAQ UNIVERSITY of KERBALA                                            *
* Yahoo. Mail     : zahraa_hashim1992@yahoo.com                                           *
*******************************************************************************************
```

Clear everything from command windows.

```
clear all; clc; close all;
```

Inter the constant data from excel file.

```
   D1=xlsread('C:\Users\ALAHAD ALJADED\Desktop\run(1.2+2.2).xlsx', 1 ,'A1:E66');
   % name of sheet Excel importing to this program
   x1=D1(:,1);                  % independent variable.
   y1=D1(:,2);                  % dependent variable.
   y2=D1(:,3);                  % dependent variable.
   y3=D1(:,4);                  % dependent variable.
   y4=D1(:,5);                  % dependent variable.
   % for first curve fitting (x1,y1).
   n=5;
   a=polyfit(x1,y1,n);
   mn=min(x1);
```

```
mx=max(x1);
xx1=(mn:(mx-mn)/100:mx);
yy1=polyval(a,xx1);
fig =figure ();
set(fig,'color','white');
axis([100 800  0  900]);
grid on
hold on
xlabel('Total weight of the full-trailer truck W ( kN )','fontsize',11);
ylabel('Truck equivalence factor','fontsize',11);
plot(xx1(1:skip:end), yy1(1:skip:end),['-kv'],'linewidth',1,'MarkerSize'...
     , 5,'MarkeredgeColor','k', 'MarkerFaceColor', 'g');
grid on
hold on
title('Total weight of the truck (W) vs Truck equivalence factor (TEF)','linewidth',2);
legend('uphill slope =','6%','12%','18%');
% for second curve fitting (x1,y2).
n=5;
a=polyfit(x1,y2,n);
mn=min(x1);
mx=max(x1);
xx1=(mn:(mx-mn)/100:mx);
yy2=polyval(a,xx1);
figure(1);
plot(xx1(1:skip:end), yy2(1:skip:end),['-ks'],'linewidth',1,'MarkerSize'...
    , 5,'MarkeredgeColor','k', 'MarkerFaceColor', 'g');
grid on
hold on
title('Total weight of the truck (W) vs Truck equivalence factor (TEF)');
legend('uphill slope = 0%','6%','12%','18%');
% for third curve fitting (x1,y3).
n=5;
a=polyfit(x1,y3,n);
mn=min(x1);
mx=max(x1);
xx1=(mn:(mx-mn)/100:mx);
yy3=polyval(a,xx1);
figure(1);
plot(xx1(1:skip:end), yy3(1:skip:end),['-ko'],'linewidth',1,'MarkerSize'...
    , 5,'MarkeredgeColor','k', 'MarkerFaceColor', 'g');
grid on
hold on
title('Total weight of the truck (W) vs Truck equivalence factor (TEF)');
legend('uphill slope = 0%','6%','12%','18%');
% for the fourth curve fitting (x1,y4).
n=5;
a=polyfit(x1,y4,n);
mn=min(x1);
mx=max(x1);
xx1=(mn:(mx-mn)/100:mx);
yy4=polyval(a,xx1);
figure(1);
plot(xx1(1:skip:end), yy2(1:skip:end),['-kp'],'linewidth',1,'MarkerSize'...
    , 5,'MarkeredgeColor','k', 'MarkerFaceColor', 'g');
grid on
hold on
legend('uphill slope = 0%','6%','12%','18%');
```

F

APPENDIX F

AVERAGE TRUCK EQUIVALENCE FACTORS FOR TERMINAL LEVEL OF SERVICEABILITY OF 2

APPENDIX F

AVERAGE TRUCK EQUIVALENCY FACTORS FOR TERMINAL LEVEL OF SERVICEABILITY OF 2

The average truck equivalency factors of full-trailer truck types 1.2+2.2, 1.2+2.22, 1.22+2.2, 1.22+2.22, 11.2+2.2, and 11.22+2.22 on uphill flexible pavements based on the truck equivalency factors of all trucks of the same group (see equation 4.30),are given below in Tables (F.1 to F.6) respectively for p_t of 2.

Table (F.1) Average truck equivalency factors for full-trailer trucks of type 1.2+2.2 for p_t=2.

H/B	Uphill slope(%)	Structural Number, SN					
		1	2	3	4	5	6
0.2	0	49.36	47.56	43.29	39.38	38.38	39.59
	12	55.51	53.45	48.53	43.95	42.63	43.85
	16	61.55	59.23	53.67	48.43	46.78	48.00
	18	67.22	64.65	58.49	52.62	50.65	51.85
0.4	0	49.36	47.56	43.29	39.38	38.38	39.59
	12	59.19	56.97	51.66	46.69	45.18	46.42
	16	70.10	67.41	60.96	54.80	52.71	53.94
	18	81.69	78.51	70.84	63.41	60.69	61.86
0.6	0	49.36	47.56	43.29	39.38	38.38	39.59
	12	63.21	60.82	55.09	49.69	47.98	49.22
	16	80.10	76.99	69.50	62.26	59.65	60.87
	18	99.58	95.64	86.11	76.76	73.08	74.19
0.8	0	49.36	47.56	43.29	39.38	38.38	39.59
	12	67.58	65.01	58.83	52.95	51.02	52.27
	16	91.65	88.05	79.35	70.88	67.66	68.85
	18	121.23	116.37	104.59	92.90	88.04	89.03
1.0	0	49.36	47.56	43.29	39.38	38.38	39.59
	12	72.32	69.54	62.87	56.48	54.31	55.56
	16	104.84	100.68	90.61	80.71	76.79	77.94
	18	147.02	141.07	126.60	112.12	105.83	106.62

Table (F.2) Average truck equivalency factors for full- trailer trucks of type 1.2+2.22 for p_t=2.

H/B	Uphill slope(%)	Structural Number, SN					
		1	2	3	4	5	6
0.2	0	72.50	69.73	63.08	56.70	54.45	55.58
	12	83.79	80.55	72.71	65.07	62.18	63.22
	16	95.33	91.59	82.54	73.62	70.05	70.98
	18	106.65	102.42	92.17	81.99	77.74	78.53
0.4	0	72.50	69.73	63.08	56.70	54.45	55.58
	12	88.56	85.11	76.77	68.60	65.41	66.39
	16	106.88	102.65	92.37	82.17	77.88	78.64
	18	126.83	121.74	109.36	96.94	91.44	91.90
0.6	0	72.50	69.73	63.08	56.70	54.45	55.58
	12	93.85	90.17	81.27	72.51	69.00	69.91
	16	120.60	115.78	104.06	92.33	87.21	87.76
	18	152.13	145.96	130.92	115.70	108.65	108.69
0.8	0	72.50	69.73	63.08	56.70	54.45	55.58
	12	99.66	95.73	86.22	76.81	72.95	73.77
	16	136.57	131.07	117.67	104.17	98.08	98.39
	18	182.82	175.34	157.09	138.47	129.55	129.07
1.0	0	72.50	69.73	63.08	56.70	54.45	55.58
	12	106.00	101.80	91.62	81.50	77.26	78.00
	16	154.86	148.57	133.25	117.73	110.54	110.56
	18	219.28	210.25	188.17	165.52	154.37	153.24

Table (F.3) Average truck equivalency factors for full- trailer trucks of type 1.22+2.2 for p_t=2.

H/B	Uphill slope (%)	Structural Number, SN					
		1	2	3	4	5	6
0.2	0	28.68	27.75	25.58	23.80	23.71	24.70
	12	29.71	28.73	26.45	24.54	24.41	25.43
	16	30.52	29.50	27.12	25.12	24.94	25.98
	18	31.05	30.00	27.55	25.47	25.26	26.32
0.4	0	28.68	27.75	25.58	23.80	23.71	24.70
	12	31.08	30.05	27.62	25.56	25.37	26.43
	16	33.77	32.61	29.89	27.55	27.25	28.37
	18	36.53	35.25	32.23	29.59	29.18	30.36
0.6	0	28.68	27.75	25.58	23.80	23.71	24.70
	12	32.69	31.58	28.98	26.76	26.51	27.60
	16	37.93	36.60	33.44	30.66	30.21	31.41
	18	43.98	42.39	38.60	35.20	34.50	35.82
0.8	0	28.68	27.75	25.58	23.80	23.71	24.70
	12	34.53	33.35	30.56	28.14	27.81	28.94
	16	43.01	41.46	37.77	34.48	33.82	35.12
	18	53.49	51.49	46.73	42.36	41.26	42.71
1.0	0	28.68	27.75	25.58	23.80	23.71	24.70
	12	36.61	35.34	32.33	29.69	29.29	30.46
	16	49.03	47.22	42.92	39.01	38.10	39.49
	18	65.19	62.70	56.74	51.16	49.54	51.11

Table (F.4) Average truck equivalency factors for full- trailer trucks of type 1.22+2.22 for p_t=2.

H/B	Uphill slope (%)	Structural Number, SN					
		1	2	3	4	5	6
0.2	0	17.19	16.74	15.74	15.05	15.21	15.75
	12	18.01	17.53	16.43	15.66	15.80	16.37
	16	18.76	18.24	17.06	18.24	16.33	16.94
	18	19.39	18.84	17.58	18.84	16.76	17.40
0.4	0	17.19	16.74	15.74	15.05	15.21	15.75
	12	18.20	17.71	16.59	15.79	15.93	16.51
	16	19.50	18.95	17.68	16.75	16.85	17.50
	18	20.96	20.33	18.91	17.82	17.90	18.60
0.6	0	17.19	16.74	15.74	15.05	15.21	15.75
	12	18.56	18.05	16.89	16.05	16.18	16.78
	16	20.85	20.23	18.82	17.75	17.83	18.54
	18	23.78	23.03	21.32	19.97	19.98	20.79
0.8	0	17.19	16.74	15.74	15.05	15.21	15.75
	12	19.07	18.54	17.32	16.43	16.54	17.17
	16	22.75	22.05	20.44	19.19	19.24	20.01
	18	27.75	26.84	24.72	22.99	22.92	23.87
1.0	0	17.19	16.74	15.74	15.05	15.21	15.75
	12	19.74	19.17	17.88	16.92	17.03	17.68
	16	25.17	24.37	22.52	21.04	21.03	21.90
	18	32.82	31.70	29.07	26.86	26.66	27.78

Table (F.5) Average truck equivalency factors for full-trailer trucks of type 11.2+2.2for p_t=2.

H/B	Uphill slope (%)	Structural Number, SN					
		1	2	3	4	5	6
0.2	0	142.94	137.28	123.62	110.27	105.16	107.09
	12	160.83	154.41	138.88	123.54	117.36	119.09
	16	178.58	171.41	154.00	136.68	129.41	130.89
	18	195.53	187.63	168.43	149.21	140.87	142.05
0.4	0	142.94	137.28	123.62	110.27	105.16	107.09
	12	175.42	168.39	151.32	134.37	127.33	128.90
	16	211.88	203.29	182.39	161.38	152.12	153.17
	18	251.29	241.02	215.97	190.56	178.85	179.24
0.6	0	142.94	137.28	123.62	110.27	105.16	107.09
	12	191.29	183.58	164.85	146.14	138.15	139.54
	16	250.76	240.51	215.53	190.21	178.59	179.09
	18	320.59	307.37	275.04	241.93	225.96	225.22
0.8	0	142.94	137.28	123.62	110.27	105.16	107.09
	12	208.48	200.04	179.50	158.89	149.87	151.05
	16	295.73	283.57	253.87	223.55	209.17	208.98
	18	405.32	388.49	347.25	304.71	283.48	281.17
1.0	0	142.94	137.28	123.62	110.27	105.16	107.09
	12	227.07	217.83	195.35	172.67	162.53	163.47
	16	347.37	333.01	297.88	261.82	244.26	243.17
	18	507.60	486.41	434.42	380.48	352.82	348.42

Table (F.6) Average truck equivalency factors for full- trailer trucks of type 11.22+2.22 for p_t=2.

H/B	Uphill slope (%)	Structural Number, SN					
		1	2	3	4	5	6
0.2	0	17.35	16.89	15.85	15.07	15.16	15.70
	12	18.76	18.24	17.05	16.12	16.17	16.77
	16	20.12	19.54	18.20	17.13	17.14	17.79
	18	21.38	20.74	19.26	18.05	18.01	18.70
0.4	0	17.35	16.89	15.85	15.07	15.16	15.70
	12	19.50	18.95	17.68	16.67	16.69	17.32
	16	22.08	21.42	19.87	18.59	18.53	19.24
	18	24.98	24.20	22.34	20.75	20.58	21.37
0.6	0	17.35	16.89	15.85	15.07	15.16	15.70
	12	20.40	19.82	18.45	17.34	17.33	17.99
	16	24.69	23.92	22.09	20.54	20.39	21.17
	18	30.04	29.03	26.65	24.54	24.20	25.13
0.8	0	17.35	16.89	15.85	15.07	15.16	15.70
	12	21.47	20.83	19.35	18.14	18.09	18.78
	16	27.94	27.03	24.87	22.98	22.72	23.60
	18	36.57	35.29	32.23	29.47	28.90	29.96
1.0	0	17.35	16.89	15.85	15.07	15.16	15.70
	12	22.69	22.00	20.39	19.05	18.96	19.69
	16	31.84	30.76	28.20	25.92	25.53	26.50
	18	44.65	43.02	39.13	35.57	34.70	35.92

The average truck equivalency factors on uphill flexible pavements based on average weight(mixed loaded and empty) of each type of full-trailer trucks, H/B ratio of 1, p_t of 2 are summarized below in Table (F.7).

Table (F.7) The average Truck equivalency factor depending on average truck weight (case; 1.2+2.2, 1.2+2.22, 1.22+2.2, 1.22+2.22, 11.2+2.2, 11.22+2.22 full-trailer trucks, H/B=1, p_t=2.0).

Full-trailer truck type	Average truck weight (kN)	Uphill slope (%)	Structural Number, SN					
			1	2	3	4	5	6
1.2+2.2	450	0	33.37	32.25	29.64	27.48	27.31	28.48
		6	48.93	47.15	29.64	39.13	27.31	28.48
		12	71.47	68.74	29.64	56.01	27.31	28.48
		18	101.13	97.14	29.64	78.19	27.31	28.48
1.2+2.22	538	0	42.47	40.98	37.47	34.36	33.77	35.08
		6	61.68	59.38	53.84	48.62	47.03	48.47
		12	89.71	86.20	77.73	69.47	66.38	67.81
		18	126.58	121.51	109.19	96.93	91.78	92.98
1.22+2.2	523	0	16.01	15.61	14.75	14.22	14.46	14.98
		6	20.78	20.18	18.80	17.81	18.02	18.82
		12	28.17	27.24	25.11	23.45	23.57	24.73
		18	37.69	36.37	33.29	30.74	30.66	32.21
1.22+2.22	592	0	13.78	13.47	12.83	12.47	12.69	13.07
		6	15.72	15.32	14.45	13.89	14.10	14.62
		12	19.94	19.36	18.05	17.11	17.30	18.04
		18	25.90	25.07	23.16	21.69	21.81	22.83
11.2+2.2	645	0	105.09	101.05	91.35	82.20	79.35	81.74
		6	169.45	162.68	146.25	130.00	123.51	125.59
		12	262.63	251.88	225.68	199.12	187.09	188.07
		18	387.76	371.68	332.33	291.89	272.18	271.03
11.22+2.22	660	0	13.36	13.08	12.47	12.11	12.28	12.65
		6	17.22	16.77	15.75	14.99	15.11	15.69
		12	24.25	23.50	21.75	20.31	20.30	21.20
		18	34.32	33.14	30.35	27.95	27.69	28.94

الخلاصة

أن تزايد الطلب على النقل بسرعة ادى الى انتشرت آثار الطرق على نطاق واسع في المناطق التي كان يتعذر الوصول إليها في السابق، ولا سيما المناطق الجبلية. حيث إن الطرق ليست دائما مستوية. العراق مثله مثل باقي دول العالم، يمتلك طوبغرافية مختلفة. حيث انه يحتوي على طرق و تقاطعات متعددة المستويات ذات ميول صاعدة مختلفة. من ناحية اخرى، معاملات آشتو ألمكافئة للحمولات المحورية معروفة للأرصفة المستوى فقط. ولهذا الغرض، تهدف هذه الدراسة إلى تحديد زيادة التلف في التبليط المرن في الميول الصاعدة الناتجة من المركبات نوع قاطرة ومقطورة.

تقدم هذه الرسالة دراسة حقلية ونظرية شاملة حول زيادة التلف في التبليط المرن في الميول الصاعدة الناتجة عن ست انواع من المركبات نوع قاطرة ومقطورة. تم اجراء مسح للحمولة المحورية لتسع وثمانين مركبة من نوع قاطرة ومقطورة ذات المحور ألامامي المزدوج، وذلك باستعمال محطات الوزن الثابتة في محافظات كربلاء والحلة، تم جمعها مع بيانات متوفرة من مسوحات لبحث سابق غطت 254 مركبة نوع قاطرة ومقطورة. ومن خلال مسح الحمولة المحورية، أجريت قياسات للمسافة بين مرتكز الأطارات الأمامية و الخلفية وغيرها من الخصائص الهندسية لكل وحدة من كل شاحنة شملهم المسح للوصول إلى النطاق المناسب من نسبة ارتفاع مركز الثقل إلى المسافة بين مراكز الأطارات الأمامية والخلفية لكل وحدة قاطرة ووحدة مقطورة لكل شاحنة شملها المسح.

لتحديد النطاق الممكن لميل للتبليط الصاعد، أجري مسح للميول الصاعدة لطريق عين التمر والعديد من التقاطعات المتعددة المستويات في مدينة كربلاء. وبالإضافة إلى ذلك، تم الحصول على بعض البيانات للميول الصاعدة لعدة طرق في مدن دهوك والسليمانية واربيل من مسوحات سابقة.

نتيجة لأعادة توزيع الحمولات المحورية على التبليط ذي الميول الصاعدة، تم حساب الأحمال المحورية على الميول الصاعدة، على افتراض ان الحركة منتظمة. وقد تحقق ذلك من خلال اخذ تأثيرات العزم الذي تولده مركّبة الوزن الموازية للميل الصاعد والواقعة في مركز الثقل لكل وحدة من وحدات شاحنة نوع قاطرة و مقطورة، وكذلك العزم الناتج عن قوة السحب المتولدة في القضيب بين وحدة القاطرة والمقطورة.

لأيجاد معاملات آشتو ألمكافئة للحمولات المحورية المحسوبةعلى التبليط ذي الميل الصاعد، تم تطوير برنامج حاسبة كتب بلغة الماتلاب وسمي (FEFUF). وباستخدام هذا البرنامج، تم تطوير مجموعة

من المخططات التصميمية الخاصة بالمعاملات ألمكافئة للمركبات على التبليط المرن ، لميل صاعد 0٪، 6٪، 12٪ و 18٪، وقد طورت هذه المخططات للستة انواع من المركبات نوع قاطرة ومقطورة التي هي قيد الدراسة. تم تطوير هذه المخططات التصميمية لمستوى الخدمة النهائي 2.5، ثلاث قيم للرقم الانشائي للتبليط المرن 2، 4 و 6 و خمس قيم لنسبة ارتفاع مركز الثقل (H) إلى المسافة بين المحاور الامامية والخلفية (B) وهي 0.2، 0.4، 0.6، 0.8 و 1. وقد بينت هذه المخططات التصميمية أن التأثير ألاتلافي للمركبات نوع قاطرة ومقطورة على التبليط المرن في الميول الصاعدة أكبر مما هو عليه على التبليط المستوي لجميع قيم الرقم الانشائي. وينطبق هذا بشكل خاص على المركبات نوع قاطرة ومقطورة ذات المحاور الخلفية المفردة في كل من وحدة القاطرة والمقطورة.

تم ايجاد متوسط المعامل المكافيء لكل نوع من انواع القاطرة والمقطورة وجدولتها. ولقد تم أعداد هذه الجداول لميول صاعدة 0٪، 6٪، 12٪ و 18٪ ، ولقيمتين من مستوى الخدمة النهائي 2.0 و 2.5 ولستة قيم للرقم الانشائي للتبليط المرن وهي 1،2، 3، 4 ، 5 و 6 و لخمس قيم لنسبة ارتفاع مركز الثقل إلى المسافة بين المحاور الامامية والخلفية وهي 0.2، 0.4، 0.6، 0.8 و 1.0.

ان هذه الرسالة تكشف عن التأثيرات الواضحة للميل الصاعد للتبليط، لنوع المركبة قاطرة ومقطورة، للرقم الانشائي ولنسبة H/B على المعاملات المكافئة للمركبة. وبالإضافة إلى ذلك، فأن هذه الرسالة تكشف عن الزيادة الواضحة في سمك التبليط المرن مع زيادة الميل الصاعد خصوصا لقاطرة و مقطورة من نوع 2.2 + 11.2، وتوصي بأستخدام المحاورالخلفية المزدوجة لكل من وحدة القاطرة والمقطورة لتقليل التأثير الأتلافي للشاحنات نوع قاطرة و مقطورة على التبليط المرن في الميول الصاعدة.

جمهورية العراق
وزارة التعليم العالي والبحث العلمي

جامعة كربلاء
كلية الهندسة / قسم الهندسة المدنية

زيادة التأثير الإتلافي على الميول الصاعدة للتبليط المرن من المركبات نوع قاطرة ومقطورة

رسالة مقدمة إلى
قسم الهندسة المدنية في جامعة كربلاء
كجزء من متطلبات نيل شهادة الماجستير
في علوم هندسة مدنية (البنى التحتية)

من قبل الطالبة
زهراء هاشم ماشاء الله الهاشمي
بكلوريوس هندسة مدنية / جامعة كربلاء 2014

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١٤٣٨محرم **٢٠١٧أكتوبر**