Assessment of Traffic Data for Road Rehabilitation Design: A Case Study of the Korogwe-Mombo Road Section in Tanzania

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ABSTRACT: Traffic loading is one of key inputs for new and rehabilitation designs of pavement. Heavy vehicles cause the most structural damage to pavements; hence, as part of the pavement design process, heavy vehicle volume, and axle load surveys are typically carried out to assist with the accurate estimation of the cumulative traffic loading over a design period. Traffic volumes, axle loads, and the ultimate cumulative traffic loading often fluctuate due to factors such as varying motorist population and economic activities along the length of the road. This paper presents a comparative assessment of traffic loading estimated for the rehabilitation design in 2005, and the actual measured site-specific traffic loading in 2015. The design traffic loading was also compared with the projected future traffic loading for the Korogwe-Mombo road section along the T2 trunk road that connects Tanzania's business hub of Dar es Salaam with the northern regional cities. The study found, inter alia, that the cumulative traffic loading based on the 2015 measured site-specific traffic data is approximately 2.8 times higher than the design traffic loading based on the 2005 traffic data, which illustrates the importance of using accurate and reliable site-specific traffic data during pavement design. The implications of the findings for rehabilitation design are presented in this paper, along with discussions on the contribution of heavy traffic loading to rutting/permanent deformation that occurred on the surface asphalt layer along the Korogwe-Mombo road section. To improve the accurate determination of traffic loading, traffic studies should ideally be conducted over a long period (typically over one year). However, this is not practical and cost effective when traditional manual methods are used. Hence, it is recommended that road agencies should consider the use of portable automated traffic and Weigh-In-Motion (WIM) monitoring systems.

Keywords: Pavement, Traffic, Weight, Axle load, Weigh-In-Motion (WIM), Rutting.

INTRODUCTION

The structural objective of a road pavement structure is to protect the underlying (weaker) layers such as subgrade against the effect of traffic loading, whereas the functional objective is to provide smooth riding quality to vehicles. Although pavement deterioration may be caused by such factors as poor quality of construction, supervision, design and materials, as well as adverse effect of climatic conditions, volumes of heavy vehicle and magnitude of axle loads are considered to be among the primary cause of deterioration of pavement structural and functional integrity. As such, heavy vehicle loading has traditionally been used as one of the key input for new and rehabilitation design of pavements [1-2]. Pavement damages caused by heavy vehicles depend not only on the Gross Vehicle Mass (GVM), but also on the distribution of vehicle mass (weight) into the pavement. The latter in turn depends on several factors, such as the number of axles on the vehicle, axle and wheel configuration, as well as the axle load magnitude, tyre inflation pressure, and tyre-pavement contact stresses [3-10]. As part of the pavement design process, surveys of heavy vehicle volumes and axle loads are conducted to assist with the estimation of the future traffic loading over a pavement design period – typically 20 years for most flexible pavements [7-13]. The estimated traffic loading is used to determine the appropriate pavement design by interactively taking into account the available material type and prevailing climatic conditions. However, traffic volumes, axle loads, and ultimately, the cumulative traffic loading are often not uniform along the length of the road due to varying motorist population and economic activities.

In 2005, the Tanzania National Roads Agency (TANROADS) identified a need for the rehabilitation of the Korogwe-Mombo road section (40 km long). The Korogwe-Mombo road section forms part of the North-East corridor (T2 trunk road), which is the main trunk road that connects Tanzania’s East Coast (including Dar es Salaam city and Tanga Port) with the northern regional cities. The rehabilitation design of the road section was undertaken in 2006, based on traffic counts and axle load surveys carried out in 2005 [14]. The rehabilitation (rehab) was initially planned to be completed in 2008. However, several constraints delayed it, and the rehab works only started in 2012 and were completed in 2014. Follow-up traffic counts and axle load surveys were carried out in 2015 after the road had been opened to traffic for a period of approximately one year. The 2005 together with the 2015 traffic counts and axle load surveys constitute the basic data for this paper.

The objective of the study presented in this paper was to conduct a comparative assessment of the initial traffic loading estimated during the rehabilitation design phase in 2005, and the actual traffic loading determined after construction completion and the opening of the road to traffic in 2015. The design traffic loading was also compared with the projected future traffic loading. The assessment provided an indication of the adequacy of the designed pavement structure and its expected future performance, and also highlighted the importance of measuring site-specific and accurate traffic volume and axle loading data.

OVERVIEW OF TRAFFIC COUNTS AND AXLE LOAD SURVEYS

Traffic Counts

Traffic counts for pavement design purposes can be performed by manual or automatic count methods such as the use of pneumatic tube counters. Each traffic count method requires different levels of effort (with cost implications), and yields different levels of traffic detail. Regardless of the traffic count method used, the main purpose of traffic counts for pavement design is to obtain estimates of the base year traffic volumes.

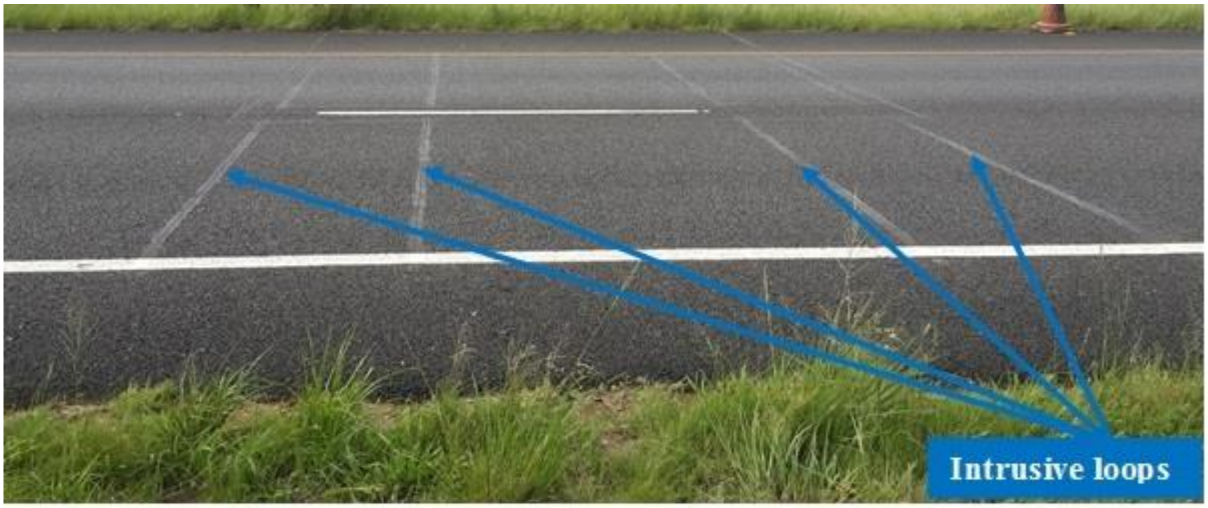
The actual composition of vehicles on a specific section along the length of the road, varies significantly, and ranges from light passenger vehicles to buses and heavy vehicles transporting commercial goods. The heavy vehicles portion of the traffic stream is generally used for pavement design purposes, because light vehicles are considered to cause insignificant damage to the pavement [1-2, 7-13]. During traffic counts, heavy vehicles are grouped into different categories to facilitate the determination of traffic loading and its contribution to pavement damage (as will be demonstrated later in this paper). For example, the current practice in Tanzania requires that heavy vehicles be grouped into four different categories, namely Medium Goods Vehicles (MGVs), Heavy Goods Vehicles (HGVs), Very Heavy Goods Vehicles (VHGVs), and Buses (see Table 1) [8].

TABLE 1 Definition of Heavy Vehicle Categories

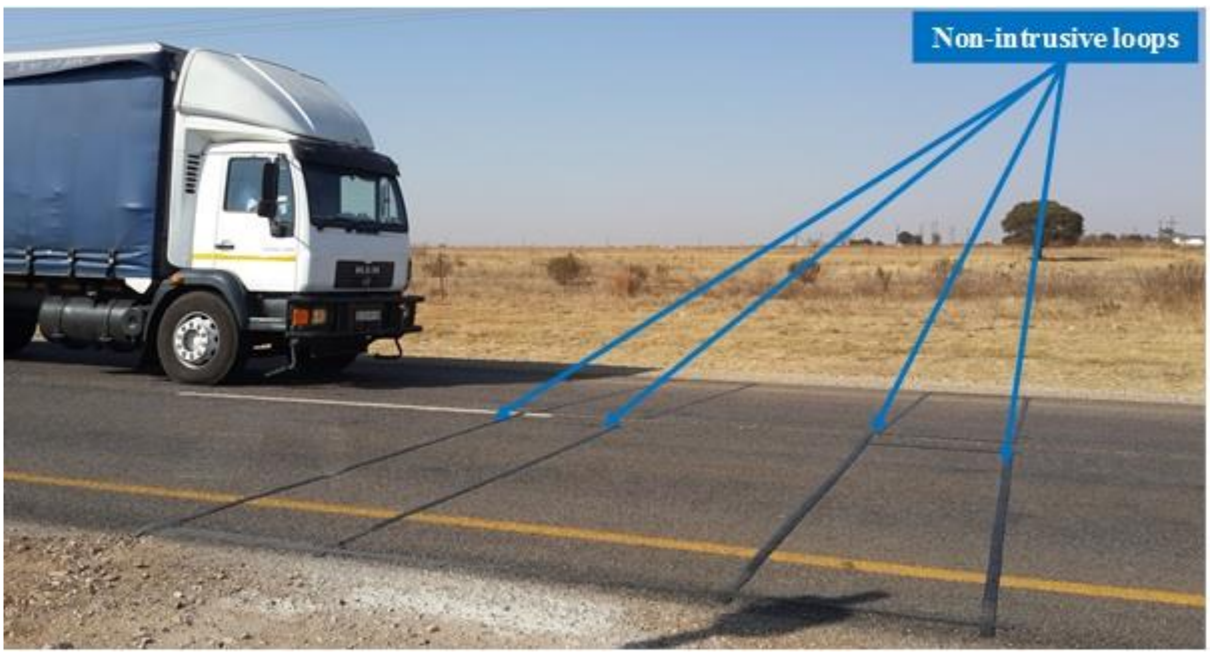
Heavy vehicle categories	Definition
Medium Goods Vehicles (MGVs)	2 axles, including steering axle, and 3 tons empty weight or more
Heavy Goods Vehicles (HGVs)	3 axles, including steering axle, and 3 tons empty weight or more
Very Heavy Goods Vehicles (VHGVs)	4 or more axles, including steering axle, and 3 tons empty weight or more
Buses	Seating capacity of 40 or more

Manual traffic counts are carried out by observers at carefully selected observation points or counting stations along a road section. The traffic count survey is usually a classified count whereby each vehicle passing an observation point is recorded on a prepared sheet/form according to the vehicle type, and each travel direction is recorded separately. The manual traffic count is usually done over a short period of time (typically seven days), as it is not practical and cost effective to undertake manual traffic counts over a long period (i.e. 24-hours per day throughout the year). To improve the reliability of the traffic data counts, it has been recommended that shorter period traffic counts be undertaken during normal days (i.e. days on which traffic patterns are not significantly affected by public and school holidays, or other events) [6, 15].

Automatic traffic counts, as an alternative to the manual traffic counts can measure traffic volumes continuously over a long period and capture seasonal variation of traffic volumes [11, 16]. The commonly used automatic traffic count systems can be grouped into three broad types, namely pneumatic tubes, magnetic wire loops, and piezo systems [11]. It is important to recognize that each of the available automatic traffic counting technologies has certain limitations that must be taken into account when establishing a traffic count station. Magnetic wire loop systems are the commonly used automatic traffic count systems in Southern Africa and can generally be classified into two categories: intrusive loops (embedded or placed on the road pavement typically for long period traffic counts) and non-intrusive loops (placed on the pavement surface and suitable for shorter period traffic counts) [15]. Figure 1 shows photos of typical intrusive and non-intrusive traffic count installations.



(a) Intrusive loops



(b) Non-intrusive loops

FIG. 1 Typical Intrusive and Non-intrusive Loop Systems

Axle Load Surveys

Traditionally, static weighing that uses a fixed weighbridge or a portable weigh pad (see Figure 2a) has been commonly used for the measurement of heavy vehicle axle loads. Alternatively, the measurement of heavy vehicle axle loads can be performed by Weigh-In-Motion

(WIM) systems, where bending plates (see Figure 2b) are some of the most widely used WIM systems due to their practicality and relatively accurate axle load measurement [6, 17-18]. It should, however, be mentioned that axle load measured using WIM systems involves static and dynamic load components [6, 18-19]. Most of the available pavement design methods make use of static axle load data, and as such WIM axle load data may need to be processed to eliminate the dynamic load component. It is should be emphasized here that the fixed weighbridge or portable weigh pads and WIM systems should be calibrated, properly installed, and operated by competent personnel/technicians to ensure accurate axle load data and minimize possible measurement errors.

(a) Portable static weigh pads

(b) WIM bending plates

FIG. 2 Typical Portable Static Weigh Pads and WIM Bending Plates

Heavy vehicle axle loads are also affected by other factors such as differences in the legal axle load limits in different jurisdictions, the level of enforcements, as well as mechanical design and load-carrying capacity of the vehicle. Table 2 shows the legal axle load limits for Tanzania [20], alongside the legal axle load limits for South Africa (Government Notice R225) [21] and the stipulations of the East African Community (EAC) Vehicle Load Control Act [22]. It is evident that in certain axle types/groups, the maximum permissible axle load limits for Tanzania are slightly higher than those for South Africa and the EAC. It is further noted that the maximum permissible load limit for the traditional dual tyres triple axle non-steering configuration (12 tyres) is the same as that for triple axle wide-base single (super single) tyres [6 tyres] for Tanzania (i.e., 24 tons), which may accelerate pavement damage. On the other hand, the EAC has reduced the maximum legal load limit to 22.5 tons for triple axle wide-base single tyres to compensate for the damaging effects of the wide-base tyres, while South Africa does not encourage the use of wide-base single tyres (i.e., 24 tons as the legal load for triple axle non-steering [12 tyres], regardless of whether they are normal or wide-base tyres).

Traditionally, dual tyres have been used to limit pavement damage by efficiently distributing the axle loads over a larger contact area than single tyres, hence reducing the contact stresses on the pavement. Due to economic, safety, and other benefits, there has been an increase in the use of wide-base single (super single) tyres in the trucking industry. However, research shows that wide-base single tyres are more damaging to pavements than traditional dual tyres, due partly to the smaller contact area that increases the contact stresses on the pavement [4-5, 23].

TABLE 2 Legal Axle Load Limits for Tanzania, South Africa and East African Community (EAC)

Type of axle/axle group	Number of tyres	Maximum permissible load on axle/axle group (tons)		
		Tanzania	South Africa	EAC
Single steering drive operated	2	8	7.7	-
Two steering drive operated	4	14	-	-
Single steering draw bar controlled	4	9	-	-
Single non-steering	2	8	8	8
Single non-steering	4	10	9	10
Tandem non-steering	4	12	16	-
Tandem non-steering	6	15	-	-
Tandem non-steering	8	18	18	18
Tandem steering (dolly)	8	16	-	-
Triple non-steering	10	21	-	-
Triple non-steering	12	24	24	24
Triple super single tyres	6	24	-	22.5

STUDY APPROACH

Description of the Case Study

The road section considered in this study, an approximately 40 km-long single carriageway with one lane in each direction, is located between Korogwe and Mombo towns in Tanzania's Tanga region. The Korogwe-Mombo road section forms part of the North-East corridor (T2 trunk road), which is the main trunk road that connects Tanzania's East Coast (including Dar es Salaam city and Tanga Port) with the northern regional cities of Kilimanjaro and Arusha. The T2 trunk road is also the main road that links Dar es Salaam and Nairobi, the major trade centres of Tanzania and Kenya, respectively. In addition, the road is used by heavy vehicles travelling to and from the neighboring country of Uganda.

Traffic Counts

In 2005, classified manual traffic counts were carried out along the Korogwe-Mombo road over seven consecutive days. The count was done continuously for 12 hours for the first four days, followed by 24-hour counts for the following three days. Vehicles passing the counting point were recorded separately for each direction. The traffic count data was used for rehabilitation design of the road section in 2006 [14].

The classified manual traffic counts were carried out in 2015 for the same Korogwe-Mombo road section after rehabilitation of the section had been completed and the road was opened to traffic [24]. The data set consisted of manual classified traffic counts conducted over seven consecutive days for 24 hours. During both the 2005 and 2015 traffic counts, heavy vehicles were grouped into four categories (MGVs, HGVs, VHGVs and Buses), as recommended in the Tanzania Field Testing Manual [8].

For pavement design and analysis purposes, heavy vehicle traffic count data is usually expressed in terms of the Annual Average Daily Traffic (AADT). In the current study, Equation 1 [8] used the AADT values based on 2005 traffic counts to compute the expected future traffic volumes in 2015. The traffic growth rates used for the computation of future traffic were 7.0% for Buses and 6.0% for MGVs, HGVs and VHGVs. These rates were based on the recommendations contained in Tanzania's traffic growth baseline survey report [25] as used during the rehabilitation design of the Korogwe-Mombo road.

$$Projected\ \ AADT = Initial\ \ AADT \times (1 + 0.01 \times j)^n \tag{1}$$

where: *j* is traffic growth rate (%), and *n* is the number of years between the determination of traffic volume and the projection year.

Axle Load Surveys

Similar to the traffic counts, two sets of axle load measurements were carried out in 2005 and 2015. Axle load measurements were performed over seven consecutive days for 24 hours, using portable static weigh pads. The axle load surveys grouped the heavy vehicles into four categories: MGVs, HGVs, VHGVs, and Buses. In addition to the axle load measurements, an Origin-Destination (O-D) survey was performed during the 2015 axle loads survey. The O-D survey included the type of the payload/goods transported, in an attempt to establish trends of motorist behavior and the character of economic activities along the road section.

Processing of the load survey data involves the determination of an Axle Equivalency Factor (AEF) to assist with estimating the traffic loading for pavement design and analysis. The AEF represents the damaging effect of an axle passing over a pavement section and is calculated using Equation 2, as recommended in the Tanzania Field Testing Manual [8].

$$Axle\ \ Equivalency\ \ Factor\ (AEF) = \left[\frac{Axle\ \ Load\ (kg)}{8160} \right]^{4.5} \tag{2}$$

For most pavement design purposes, the full axle load distribution is usually not available. As such, the concept of "E80 per heavy vehicle" (E80/HV) or Vehicle Equivalency Factor (VEF) is used [1-2]. VEF is a factor that converts different truck loads to an equivalent number of standard axles (i.e., 8160 kg per axle). Although the concept "E80 per heavy vehicle" is widely used in most empirical pavement design procedures, the mechanistic-based pavement design procedures currently under development or being implemented by various road agencies are shifting towards using the full axle load spectral distribution [26-28]. The use of a full axle load spectrum facilitates a more accurate and realistic characterization of traffic loading for accurate pavement design and optimal performance.

In this study, Equation 3 [8] was used to process the axle load survey data of the individual heavy vehicles to determine VEF.

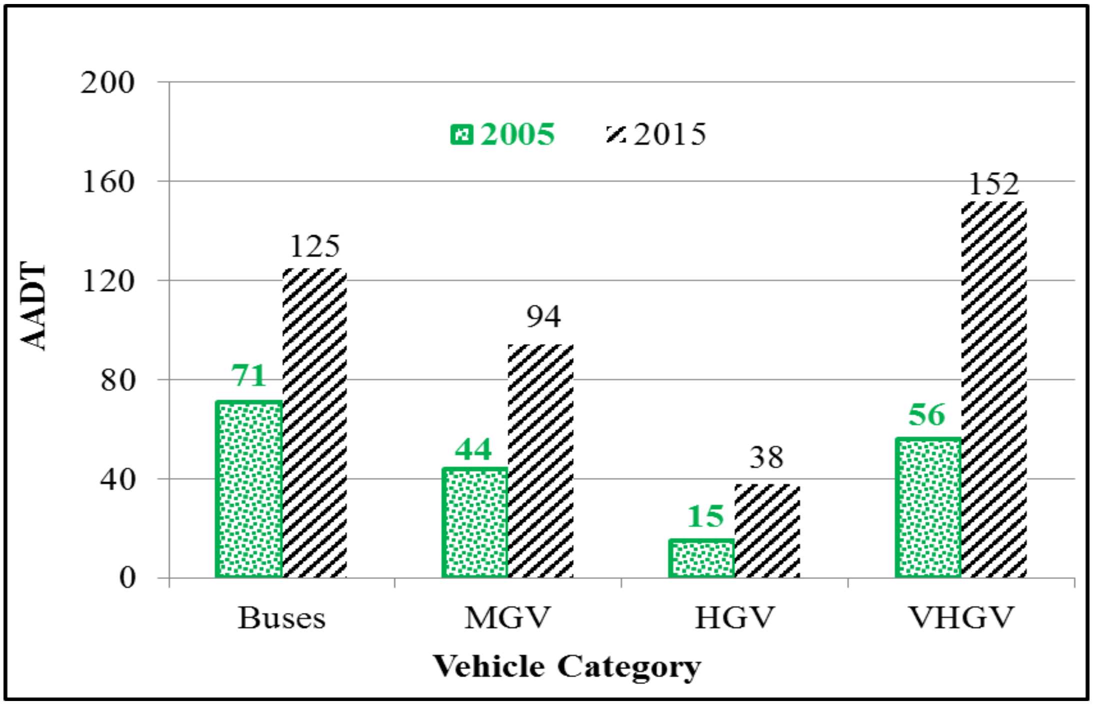
$$Vehicle\ Equivalency\ Factor\ (VEF) = \sum_{i}^{n} AEF \tag{3}$$

where: *n* is the total number of axles, and *AEF* is the Axle Equivalency Factor that was computed using Equation 2. The VEF values of each heavy vehicle were subsequently used to determine the average VEF for each of the heavy vehicle categories. The average VEF was calculated separately for each lane direction.

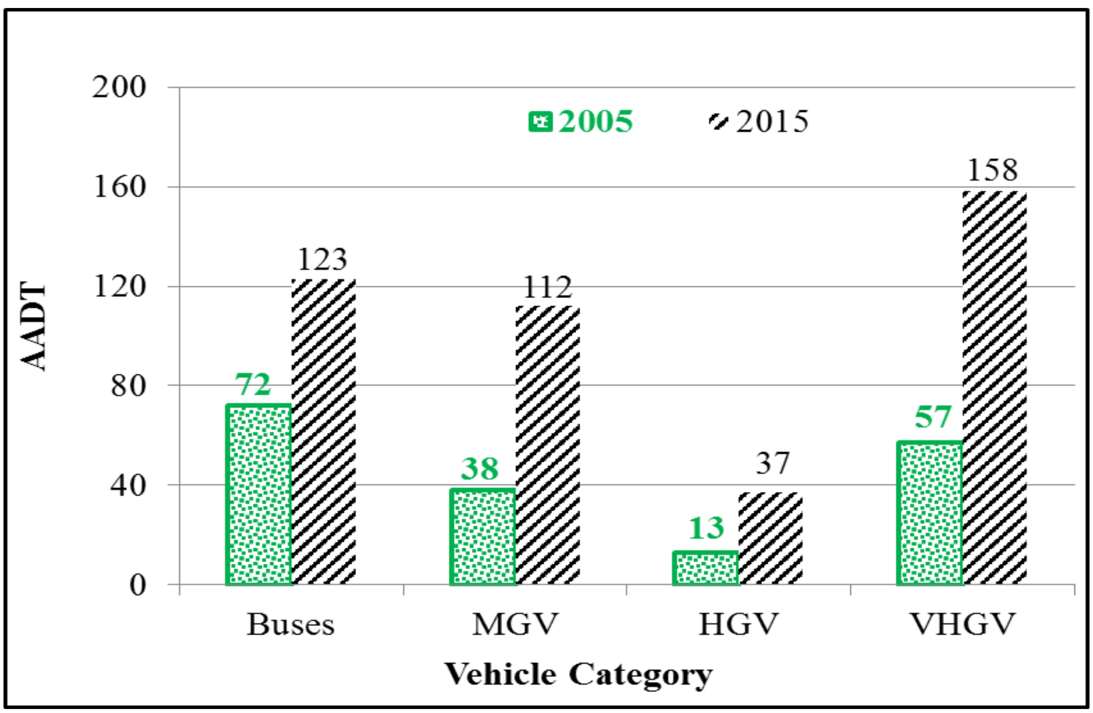
ANALYSIS RESULTS AND DISCUSSIONS

Assessment of Heavy Vehicles Volume

As mentioned earlier, for pavement design and analysis purposes, traffic count data of heavy vehicle are usually expressed in terms of the AADT. Figure 3 presents the AADT for each of the heavy vehicle categories for traffic counts carried out in 2005 and 2015, where the values for the 2015 traffic count are higher than those for 2005. For both the 2005 and 2015 traffic count surveys, the AADT in both directions appears to be similar, with the exception of the MGV category for the 2015 survey, where AADT for the Korogwe-Mombo direction was 94 and the AADT for the Mombo-Korogwe direction it was 112. The traffic count data also shows that in 2005 the AADT for Buses was highest, followed by the VHGVs, MGVs and HGVs categories. In contrast, the 2015 traffic count data indicates that the AADT for VHGVs was the highest, followed by Buses, MGVs and HGVs.



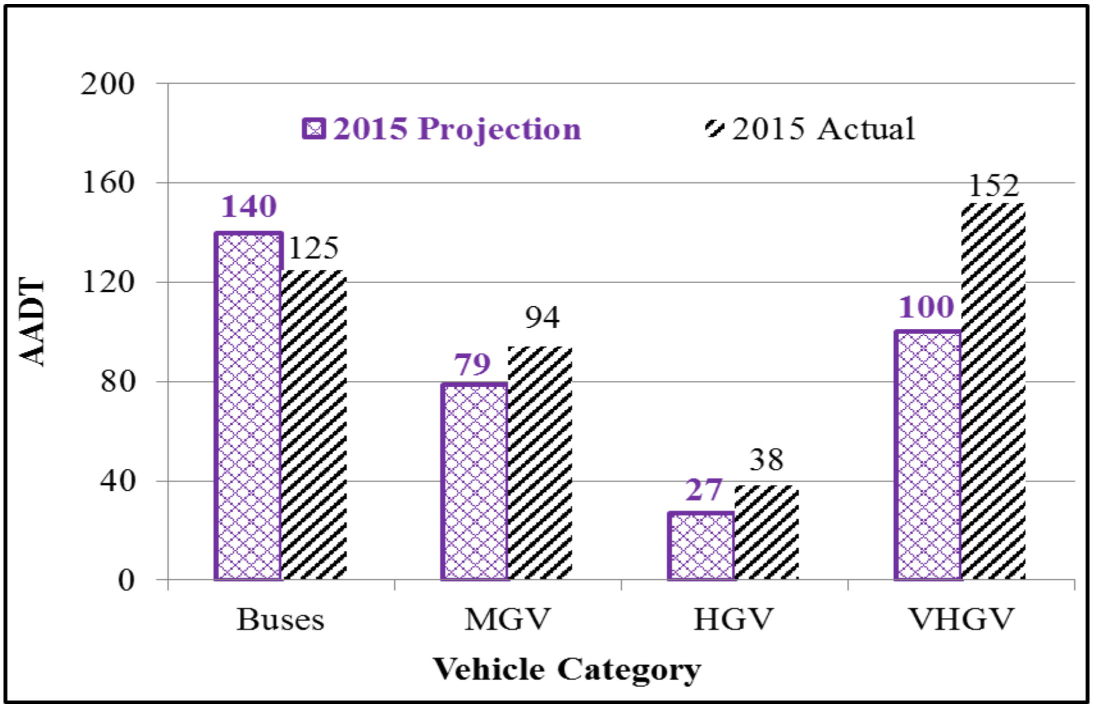
(a) Korogwe-Mombo lane direction



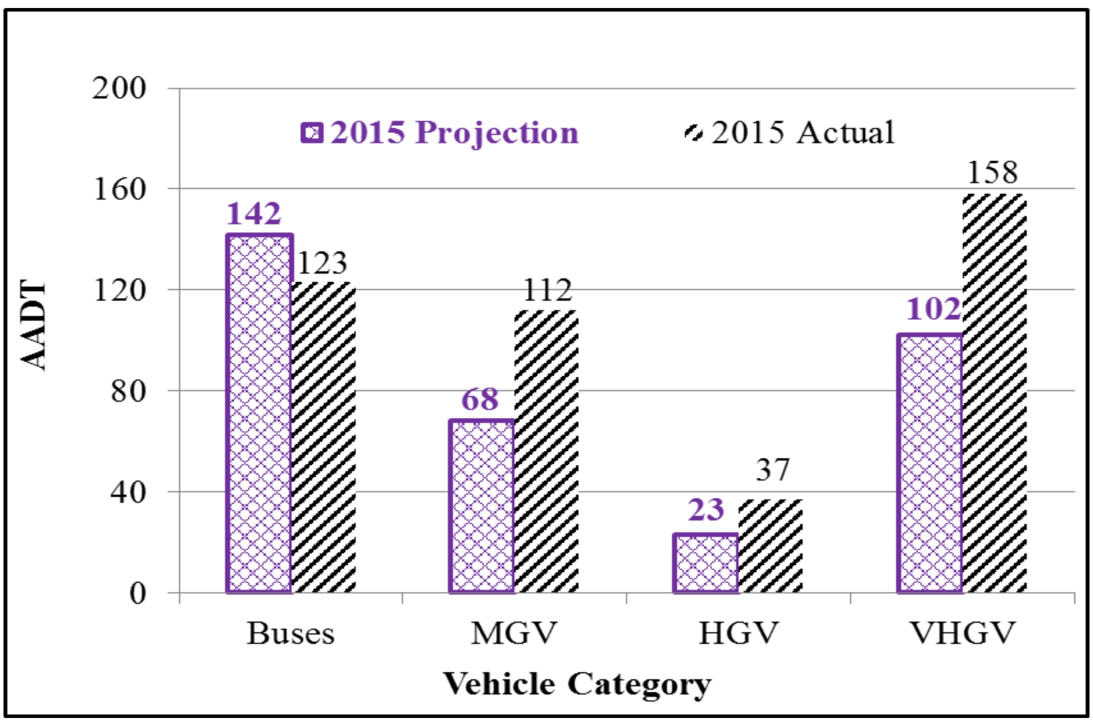
(b) Mombo-Korogwe lane direction

FIG. 3 AADT for 2005 and 2015 Traffic Counts

Figure 4 compares the actual traffic volumes obtained during the 2015 traffic counts and the volumes that were projected based on the 2005 traffic counts (using Equation 1). With the exception of Buses, the AADT projections based on the 2005 traffic count data are generally lower than the actual AADT determined on the basis of the actual 2015 survey. For instance, while the projected AADT for Buses is approximately 12% higher than the actual AADT in the Korogwe-Mombo direction, the projected AADT for MGVs, HGVs and VHGVs is lower than the actual AADT by approximately 16%, 29% and 34% respectively. The difference is significantly higher for the VHGV category. The Origin-Destination (O-D) survey performed as part of the axle loads survey indicated that most of the VHGVs transport cement from the Tanga cement factory to the northern regions of Kilimanjaro and Arusha, and hence, they may not have been accounted for during the 2005 traffic counts. Additionally, the general traffic growth trends of about 76%, 114%, 153% and 171% for Buses, MGVs, HGVs, and VHGVs, respectively over a 10-year period could be a contributing factor.



(a) Korogwe-Mombo lane direction



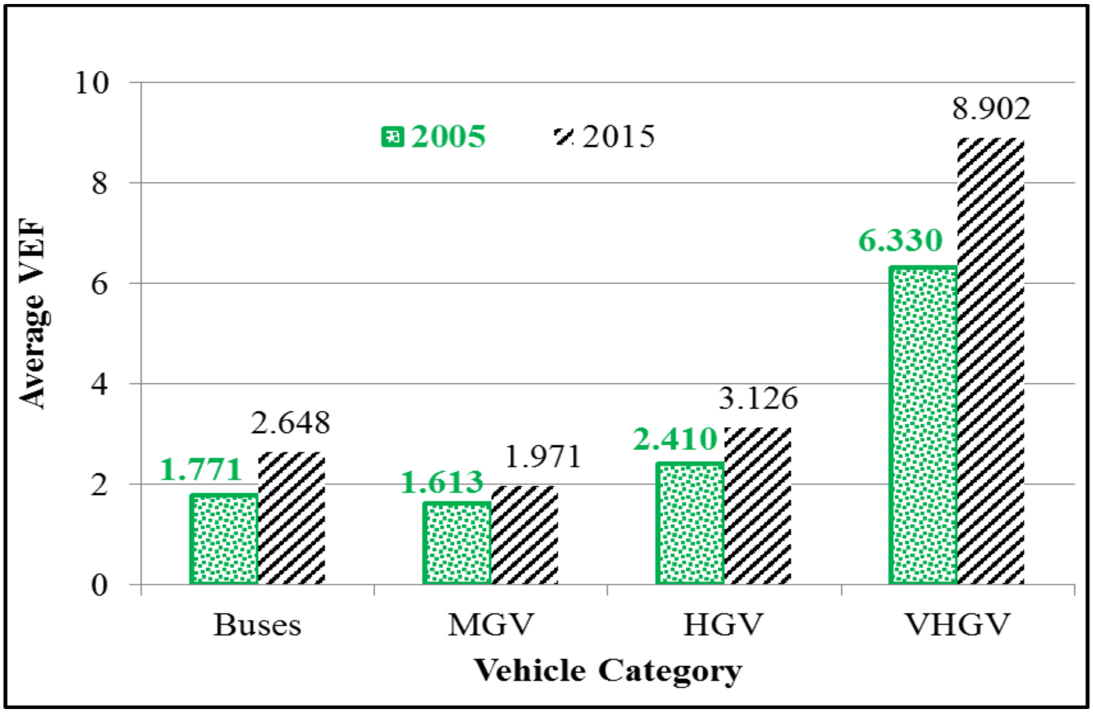
(b) Mombo-Korogwe lane direction

FIG. 4 Comparison of Actual and Projected 2015 AADT

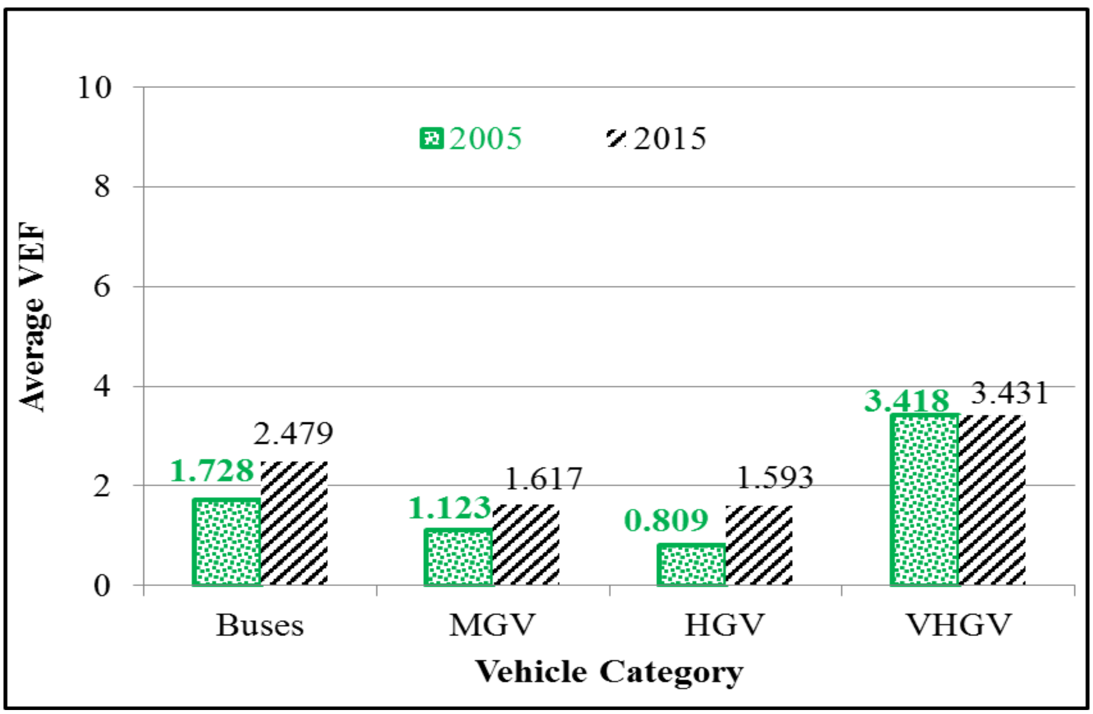
The comparison of the actual and projected traffic suggests that the generic traffic growth rates obtained from the Tanzanian traffic growth baseline survey report should be used cautiously, as they may not be realistic for some roads. It further demonstrates the need to accurately determine site-specific traffic data for pavement structural design purposes, rather than to use generic traffic growth rates derived from current empirical trends to determine the expected growth in Gross Domestic Product (GDP) of a country. It should, however, be mentioned that both the 2015 and the 2005 traffic counts were carried out over a short period (seven days). Thus, hence the effects of seasonal traffic variations may not have been accounted for, which may have resulted in huge differences. In future, traffic counts, while done over a 7-day period should be conducted intermittently during each season to minimize the seasonal variation effect, e.g., one 7-day count in summer, one 7-day count in winter, one 7-day count in the rainy season, etc.

Assessment of Axle Loads

Figure 5 compares the average VEF values for each of the heavy vehicle categories that were determined using the 2005 and 2015 axle load surveys. For both the 2005 and 2015 surveys, the VEF values determined for the Korogwe-Mombo direction are higher than those for the opposite lane direction (i.e. Mombo-Korogwe). This observation is in agreement with the O-D survey data, which indicated that the heavy vehicles travelling in the Korogwe-Mombo lane direction are loaded more heavily than those travelling in the Mombo-Korogwe direction. The O-D survey indicated that the most common loads/goods transported by the heavy vehicles was cement (mostly from the Tanga cement factory), diesel/petrol, shop supplies, wheat flour, fertilizer, gas, building materials, and farm produce. These loads were carried to the northern regions of Tanzania and neighboring countries of Kenya and Uganda. This observation demonstrates the importance of undertaking axle load surveys for each lane direction, separately, as the traffic loading in the opposite lane direction may differ significantly. It is further observed that the VEF values obtained from the 2015 surveys are higher than those determined from the 2005 survey. Hence, the VEF obtained from the 2005 axle load survey data is more likely to underestimate the cumulative pavement traffic loading, as will be shown in the next section.



(a) Korogwe-Mombo lane direction



(b) Mombo-Korogwe lane direction

FIG. 5 Average Vehicle Equivalency Factors (VEFs)

Comparison of Traffic Loading

The determined VEF values were used in combination with the AADT to determine the cumulative pavement loading (E80s). A 20-year design period was assumed, which is the same as the design period used during the rehabilitation design of the road section. The commutative pavement traffic loading was computed using traffic counts and axle load survey data for both 2005 and 2015. The cumulative pavement loading was calculated separately for each lane direction. As indicated earlier, the traffic growth rates used were 7.0% for Buses and 6.0% for MGVs, HGVs and VHGVs. The following three different scenarios were considered:

- Scenario 1: Use of the traffic counts and axle load survey data for 2005 to determine the 20-year traffic loading, with 2008 as the base year. This is similar to the approach used during the design of the rehabilitated road (i.e., the construction was originally planned to be completed by 2008).
- Scenario 2: Use of traffic counts and axle load survey data obtained in 2005, with 2015 as a base year. This means that the recommended traffic growth rates were applied to the actual 2005 traffic counts to project the AADT for the year 2015 and then compute the 20-year traffic loading.
- Scenario 3: Use of the actual traffic counts and axle load survey data for the 2015 survey to determine 20-year traffic loading.

The 2008 base year used for Scenario 1 is similar to the base year used in the rehabilitation design. On the other hand, Scenarios 2 and 3 both used 2015 as base year, but with traffic counts and axle loads survey data obtained in 2005 and 2015, respectively. This allowed for a direct comparison of the traffic loading estimated using the old (2005) and the latest (2015) traffic dataset. It should be emphasized here that despite the delayed completion of the rehabilitation construction, design revision was not done. Hence, Scenario 1 was compared with Scenarios 2 and 3 to establish the extent to which the traffic loading for the rehabilitated road has been underestimated.

Table 3 presents the calculated 20-year cumulative pavement traffic loading (E80s) for Scenarios 1 to 3 as 9.7, 14.8 and 27.2 million, respectively for the Korogwe-Mombo lane direction, and 6.0, 9.6 and 15.1 million, respectively, for the opposite lane direction (i.e. Mombo-Korogwe).

As was theoretically expected, due partly to higher traffic growth over a 10 – year period, the cumulative traffic loading calculated based on the 2015 data (Scenario 3) is significantly higher than the estimated traffic loading based on the 2005 survey data using Scenarios 1 and 2. The traffic loading in Scenario 3 was approximately 2.8 times and 1.8 times higher than in Scenarios 1 and 2 respectively for the Korogwe-Mombo direction, and approximately 2.5 times and 1.6 times higher than in Scenarios 1 and 2, respectively, for the Mombo-Korogwe lane direction). This was expected due to the higher AADT and VEF values obtained during the 2015 traffic counts and axle load surveys, respectively. The traffic loading that was computed based on the 2005 survey data may underestimate the actual expected future traffic loading, and this again illustrates the importance of using the latest, most accurate and reliable traffic data, during rehabilitation design.

TABLE 3 Cumulative Traffic Loading

Lane Direction		Korogwe-Mombo				Mombo-Korogwe			
Heavy vehicle category		**Buses**	**MGV**	**HGV**	**VHGV**	**Buses**	**MGV**	**HGV**	**VHGV**
Scenario 1	AADT	87	52	18	67	88	45	15	62
	VEF	1.771	1.613	2.410	6.330	1.728	1.123	0.809	3.418
	E80s per day	154	85	43	422	152	51	13	212
	Traffic growth rate (%)	7.0	6.0	6.0	6.0	7.0	6.0	6.0	6.0
	20 years E80s (million)	2.3	1.1	0.6	5.7	2.3	0.7	0.2	2.8
	Total E80s (million)	**9.7**				**6.0**			
Scenario 2	AADT	127	79	24	87	142	68	23	102
	VEF	1.771	1.613	2.410	6.330	1.728	1.123	0.809	3.418
	E80s per day	225	127	58	551	245	76	19	349
	Traffic growth rate (%)	7.0	6.0	6.0	6.0	7.0	6.0	6.0	6.0
	20 years E80s (million)	3.4	1.7	0.8	7.4	3.7	1.0	0.3	4.7
	Total E80s (million)	**14.8**				**9.6**			
Scenario 3	AADT	125	94	38	152	123	112	37	158
	VEF	2.648	1.971	3.126	8.902	2.479	1.617	1.593	3.431
	E80s per day	331	185	119	1353	305	181	59	542
	Traffic growth rate (%)	7.0	6.0	6.0	6.0	7.0	6.0	6.0	6.0
	20 years E80s (million)	5.0	2.5	1.6	18.2	4.6	2.4	0.8	7.3
	Total E80s (million)	**27.2**				**15.1**			

IMPLICATIONS OF THE FINDINGS

Implications for Pavement Design

According to the Tanzania Pavement and Materials Design Manual [2], the traffic loading that was computed based on the 2005 traffic counts and axle load survey data falls under Traffic Loading Class-TLC 10 (i.e., cumulative traffic loading `between 3 and 10 million E80s) for Scenario 1 and TLC 20 (between 10 and 20 million E80s) for Scenario 2. On the other hand, the outcomes of the latest traffic and axle load surveys (conducted in 2015 after construction completion and the opening of the road to traffic) indicate that the road section is more likely to carry traffic loading that is equivalent to TLC 50 (between 20 and 50 million E80s) over the 20-year design period. The rehabilitation design of the road section was undertaken using TLC 10, which may have underestimated the expected future traffic loading.

Although a detailed evaluation of the structural adequacy of the pavement structure used for the rehabilitation of the Korogwe-Mombo road section falls outside the scope of this paper, the traffic loading analyses indicate that the pavement structure may have been under-designed and may require further structural strengthening before the end of its desired 20-year service life. In addition, monitoring the long-term performance of the road section may be needed to ascertain the extent to which an inaccurate determination of the traffic loading may shorten the pavement's service life.

Implications of Traffic Loading to Pavement Performance

At the time of the traffic count and axle load surveys conducted in 2015, the Korogwe-Mombo road section had been trafficked for approximately two years. However, severe rutting/permanent deformation of the asphalt layer had occurred in certain areas as illustrated in

Figure 6, and this necessitated a forensic investigation to find the primary cause of the rutting [24]. Although the forensic investigation focused on various aspects (e.g., the quality of construction, materials, the assessment of the asphalt mixture design), of particular interest for this paper was the contribution of traffic loading to the observed surface asphalt layer rutting. Interestingly, the Korogwe-Mombo direction (the heavily loaded lane direction) had more severe rutted areas than the opposite lane direction (i.e. Mombo-Korogwe), indicating that heavy traffic loading played a role in accelerating the rutting development. As expected, rutting and shoving were also observed on most approach and departure sections of "speed-calming humps", due to higher vertical loading and shear stresses imposed by slow-moving and partially braking heavy vehicles.

FIG. 6 Rutting on Korogwe-Mombo Section after Two Years of Heavy Trafficking

Figure 7 presents the cross-sectional rut profile measurements using a straight edge at 15 m intervals around the rutted/deformed areas shown in Figure 6 (approximately 100 m long section). Figure 7 shows that maximum deformations (rutting) of 62 and 69 mm were measured on the outer and inner wheel paths, respectively. These higher permanent deformations (rutting) are unacceptable and undesirable given that the road had been trafficked for less than two years at the time of rut profile measurements. However, this extreme surface rutting may be attributed partially to traffic underestimation during the rehabilitation design, as well as to poor construction and quality control methods.

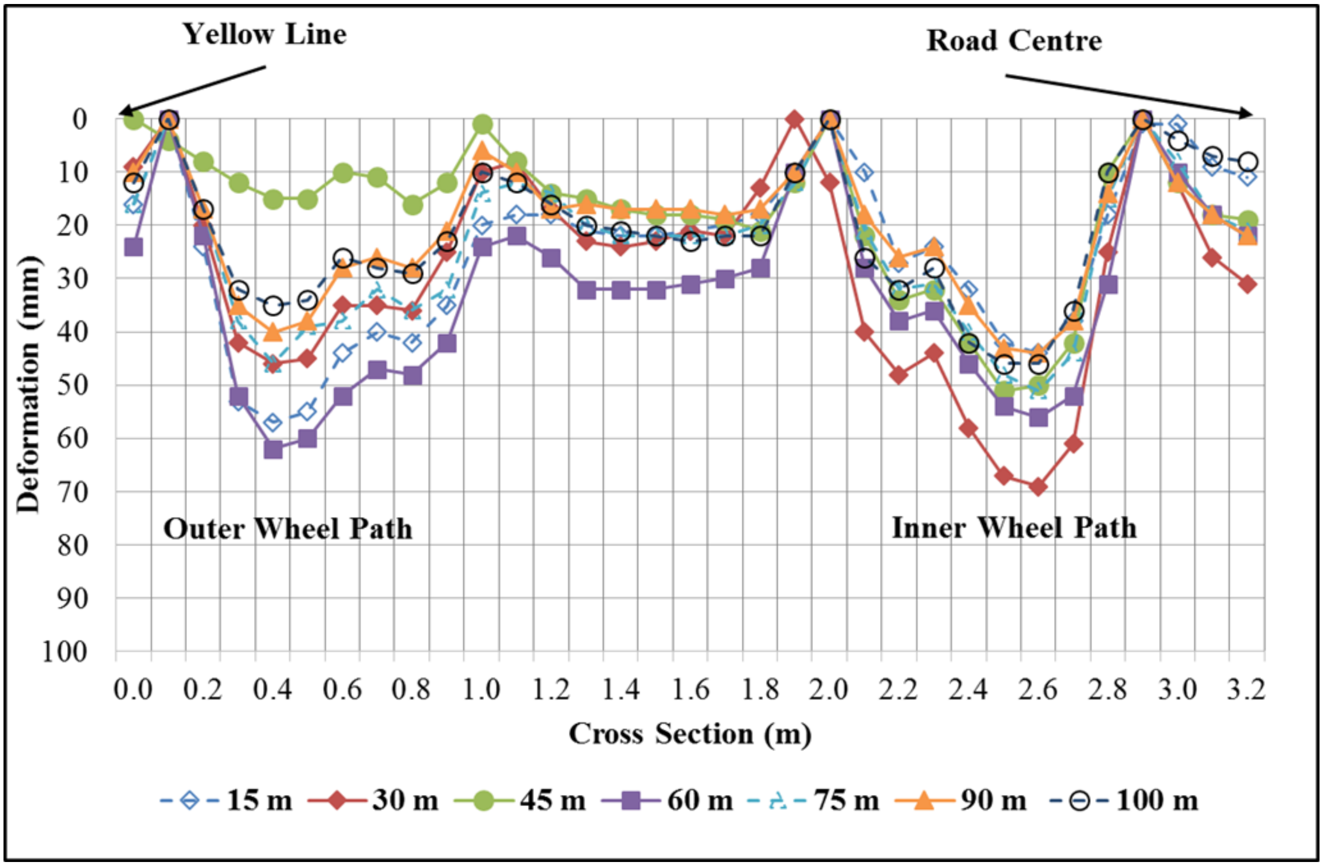


FIG. 7 Cross-Sectional Rut Profile Measurements

It is well known that rutting in asphalt layers develops in two main stages. The first stage is consolidation, which involves densification of the asphalt layer, usually accompanied by volume change, while the second stage consists of shear deformation, which is plastic flow not associated with volume change [29]. During the first stage, traffic loading causes aggregate particles to move towards their preferred orientation, which results in an increase in density or reduction in air voids. Typically, the field void content of a well-designed and well-constructed asphalt will reduce from an initial post-compacted void content (usually 6 to 8%) to a design air void content between 4 and 5%, at which stage the asphalt mixture is expected to provide optimum shear resistance to the traffic loading [29].

Monitoring the field compaction density/air voids is widely accepted as a means of Quality Control (QC) and Quality Assurance (QA) for asphalt pavement layers. As part of the forensic investigation on the Korogwe-Mombo road section [24], field asphalt core samples were extracted at four different locations (six cores for each location), and their air voids were determined in accordance with the Technical Methods for Highway 1 (TMH 1) Methods C3 [30]. The field asphalt core samples had to be extracted from where the asphalt mixture was relatively undisturbed as a result of the severe rutting, and hence the samples would represent approximately the air void content during paving.

Table 4 presents a summary of the air voids (AVs) results. Since the asphalt core samples were extracted from relatively undisturbed areas and had been trafficked for approximately two years only, relatively higher AVs were expected if the asphalt layer had been initially compacted to the desired AVs (between 6% and 8%). Surprisingly, the AVs ranged from 1.6% to 3.6%, raising questions about QC/QA process in this project, as well as about the asphalt mixture design and construction practices, which would have caused premature rutting of the asphalt layer, and then exacerbated by other factors such as heavy traffic loading [24].

TABLE 4 Summary of Air Voids Content Results of Field Core Samples

Core No.	Air voids content (%)			
	Location 1	**Location 2**	**Location 3**	**Location 4**
1	1.9	2.0	3.5	2.7
2	2.0	1.8	3.1	2.7
3	2.5	2.1	3.0	2.7
4	1.6	2.0	3.0	2.9
5	1.9	2.5	3.4	2.2
6	1.8	2.0	3.6	2.5
Average	2.0	2.1	3.3	2.6
STDV	0.302	0.234	0.266	0.240
CoV (%)	15.5	11.3	8.1	9.2

CONCLUSIONS AND RECOMMENDATIONS

By using the Korogwe-Mombo road section in Tanzania as a case study, this paper presented a comparative assessment of the traffic loading estimated during the rehabilitation design, the currently measured site-specific traffic loading. The design traffic loading was also compared with the projected future traffic loading. Implications to both pavement design and performance were furthermore highlighted. Based on the results and discussions contained in this paper, the following conclusions are drawn and recommendations made:

- The assessments that were conducted demonstrated the need for good quality and reliable site-specific traffic data to ensure an accurate determination of traffic loading for pavement design purposes.

- The common practice of conducting traffic studies over a short period of time (usually seven days) may cause significant inaccuracies in the prediction of the design traffic loading due to inability to capture seasonal variation of traffic, traffic pattern changes resulting from short- to medium-term changes in economic activities, changes in transportation regulations, changes in legal axle load limits, changes in the level of traffic rule enforcements, etc.
- The generic traffic growth rates used to determine traffic loading should be applied cautiously. Traffic volumes may vary over time due to, for instance, fluctuation in economic trends. Furthermore, the growth rates should not be assumed to be the same for different highways and heavy vehicle categories, as traffic patterns may fluctuate for a specific heavy vehicle category.
- To improve the accurate determination of traffic loading, traffic studies should be conducted over longer periods. In lieu of the costly permanent WIM stations, road agencies should consider investing in the use of portable WIM systems as a practical and cost-effective means of accurately measuring site-specific traffic loading data.
- In situations where significant time delays are expected from the rehabilitation design up to the start of construction, it is recommended that updated traffic studies be conducted to ascertain the most accurate and representative traffic figures, as short- to medium-term changes in economic activities may affect traffic patterns (such as the existence of a cement factory which influenced the traffic in one lane/direction in this paper).

Overall, this study demonstrated the importance of routine traffic surveys to measure and accurately quantify the changes and growth trends in traffic patterns, both in terms of volume counts and the axle load spectrum. Instead of manual traffic surveys, the use of more accurate automated traffic and WIM-monitoring systems is strongly recommended to ensure accurate traffic data characterization for optimal pavement design, rehabilitation, and planning purposes. However, the final selection of the traffic count and axle load measurement methods should take into account other factors such as cost and the type/details of the traffic data required. In this regard, costly permanent traffic and WIM-monitoring systems can be stationed on selected highway sites, whereas portable WIM technology can offer a cost-effective alternative for the measurement of site-specific traffic data at any desired highway location.

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