

BRT AND PUBLIC TRANSPORT NETWORKS – PAVEMENT DESIGN CONSIDERATIONS FOR BUS LANES



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ABSTRACT

Bus Rapid Transit (BRT) systems or Integrated Rapid Public Transport Networks (IRPTN) are being rolled out in South Africa in at least 13 metropolises and larger municipalities. From a pavement design perspective, the design of the bus lanes requires specific attention due to the high number of wheel load repetitions that are applied in a channelized manner. Wheel loads can be very high due to bus axle loads of up to 12t. A fully loaded articulated bus has an axle equivalency factor of up to 9 equivalent standard axle loads (80kN). Typical axle loads at varying occupancy levels for standard buses, articulated buses and feeder buses and the associated number of equivalent standard axle loads per bus are provided in this paper and these can be used by pavement designers as guidance.

This paper evaluates a number of pavement design options that were developed for inter alia the Johannesburg Rea Vaya, the Rustenburg Yaron, the eThekweni Go!Durban and the Ekurhuleni Harambee. These include both flexible pavements (asphalt with and without binder modification) and rigid pavements (continuously reinforced concrete pavements). The paper provides insight into the bus volumes, cumulative traffic loading, selected pavement design options and the pavement layer materials that were selected.

Some conclusions reached in this paper are firstly that there is no fixed decision-based model that one can apply to the choice between concrete and asphalt pavements for BRT lanes, but at critical areas, such as intersections and confined CBD areas, asphalt pavements have certain advantages over concrete and secondly that there is a tendency to ignore or to overestimate bus occupancy levels, which has a significant effect on the total estimated traffic loading on BRT pavements.

INTRODUCTION

Bus Rapid Transit (BRT) systems and Integrated Rapid Public Transport Networks (IRPTN) make use of road-based vehicles. This offers a larger degree of flexibility compared to rail-based public transport system in urban areas such as train, light rail and trams, both in terms of implementing the necessary infrastructure as well as the utilisation of coaches. The initial capital investment in infrastructure required for BRT systems and IRPTNs is also considerably less than that for light rail and trams. At the same time, BRT systems and IRPTNs offer a high performance rapid transit service and are capable of moving high passenger volumes from one point to another in a fast, comfortable and reliable manner. BRT systems and IRPTNs are therefore very effective to facilitate a modal shift from private to public transport, both in terms of infrastructure spending and flexibility required for enhancing public transport networks in urban areas that are already well developed. The rapid bus services offered are well integrated with other forms of public transport and are usually branded with a quality image and unique identity.

BRT's are characterised by exclusive bus lanes that operate on trunk routes in urban transit corridors with right-of-way at intersection and in spaces shared with other modes of transport. BRT lanes are constructed in the median of the corridors. The stations are for exclusive use by the BRT buses and have elevated platforms to facilitate level boarding. This means that BRT buses are equipped with high-level doors that do not allow for street-level boarding of passengers. BRT buses can therefore

only operate on their dedicated trunk routes. Ticketing and fare collection takes place "off-board" and at the stations. The trunk routes are integrated with complementary bus feeder routes, on which "normal" buses operate under mixed traffic conditions, as well as with other modes of public transport.

The buses designed for usage of BRT trunk routes have axle loading capacities in excess of the legal permissible axle load on public roads in South Africa (10.2t for buses), with axle load capacity of fully loaded buses of up to 12t. When BRT systems operate at full system capacity, fully loaded buses with short headways, i.e. high bus frequencies, travel on trunk routes during peak hours. By virtue of the dedicated lanes and the precision docking at stations, the wheel loads on the BRT pavements are applied in a channelized manner and the lateral wander of BRT buses is much less than lateral wander of normal traffic on open roads. The high axle loads and channelized movements of the BRT buses requires a specific pavement design approach in order to ensure the bus lanes pavement perform satisfactory in terms of permanent deformation (rutting) over the full structural design period (normally 30 years for BRT pavements).

The objective of this paper is to provide guidance to municipal engineers and pavement designers to arrive at appropriate pavement design solutions for dedicated bus lanes. In doing so a number of pertinent design considerations will be discussed in this paper, including climatic environment, traffic loading, pavement design and materials, as well as certain practical considerations and limitations such as constructability, disruption to traffic and pavement maintenance requirements.

This paper will first provide a brief background on the development of BRT systems internationally and the BRT Standard followed by a brief background on the development of BRT systems and IRPTN's in South Africa over the past decade. This will be followed by a discussion of the design considerations as referred to above and some practical considerations and limitations.

DEVELOPMENT OF BUS PUBLIC TRANSPORT SYSTEMS

International developments

According to Lindau et al. 2008 the first widely recognised BRT system in the world was implemented in Curitiba, Brazil during the 1970's. It is an excellent example of how proper planning and land use development can direct the future growth of a city along transportation corridors.

FIGURE 1 Channelized bus lane traffic resulting in rutting





FIGURE 2 My CiTi system in Cape Town. Typical exclusive median-aligned BRT bus lanes

Arias et al. 2008 and Lindau et al. 2010 reported that in the 1970s, when Curitiba had only 400,000 inhabitants, plans for implementing a light rail transit system were prepared. The idea was aborted due to its high capital costs. Instead, the Institute for Research and Urban Planning of Curitiba conceived a trunk-and-feeder bus system operating along segregated median flow lanes as the central component of axial transit ways. This bus system was gradually upgraded until reaching the status of the first full BRT system in the world.

Gauthier reported in 2013 that Curitiba now has a population of nearly two million inhabitants and the metropolitan area has experienced an average annual growth of 4.6% over the past 50 years. He believes that the successful BRT system is at the core of the growth and land use development over this period. He also reported that there has been an exponential increase in the total length of BRT systems after 2000 with an increasing number of cities world-wide implementing BRT systems.

The BRT standard

In 2013 the Institute for Transportation & Development Policy (ITDP) published the BRT Standard. This BRT Standard was developed to create a common definition of bus rapid transit and to recognize high-quality BRT corridors around the world. It also functions as a technical tool to guide and encourage municipalities to consider the key features of the best BRT corridors as they move through the design process (ITDP, 2016).

In accordance with the BRT standard, there are five basic criteria that BRT systems should comply with in order to be recognised as such. These are 1) Exclusive bus lanes, 2) Median aligned infrastructure, 3) No conflicting movement / Priority at intersections, 4) Off-board fare collection and 5) Level boarding (elevated station platforms).

The ITDP also developed a BRT Scorecard and recognises systems world-wide that are accredited with gold, silver and bronze BRT standards. This scorecard takes into account six categories (BRT Basics, Service Planning, Infrastructure, Stations, Communications and Access and Integration) with penalty deductions for non-optimal operations e.g. overcrowding, low operating speeds, low bus frequencies, etc.

A typical example of the exclusive BRT bus lanes that are in the centre of the road space is shown in Figure 2 below. This figure also shows a good example of a BRT bus station, with an elevated platform facilitating level boarding and with ticketing and fare collection at the entrance of the BRT station.

Developments in South Africa

Cape Town and Johannesburg were the first cities to implement IRPTNs respectively branded “My CiTi” and “Rea Vaya”. The early / pilot phases



BRT station with raised platform and fare collection at the entrance of the station

in both cities came on-line shortly before the 2010 Soccer World Cup. In the 2013/14 financial year more than R 5 billion was spent on rapid transport networks in 13 South African cities. Besides the Cities of Cape Town and Johannesburg, these are Tshwane, eThekweni, Ekurhuleni, Rustenburg, Mangaung, Nelson Mandela, Msunduzi, Polokwane, Buffalo City, George as well as the Moloto Corridor. Progress of the various networks vary, with most of the networks having completed construction on the first phases, some already being operational, while others are still in the planning stages. The roll-out of the planned networks are such that gradually the total length of the systems will be extended by constructing and bringing into operation the next phases of the systems.

CLIMATIC ENVIRONMENT

The climatic environment of the project area affects the performance of the pavement materials as well as the performance of the pavement structure in general. Normal environmental design inputs are prevailing air temperatures (minima and maxima), surface temperatures, annual rainfall and rainfall pattern (summer vs winter rainfall area).

There is no difference in dealing with the macro-climatic region of the project area for a BRT pavement design compared to pavement design for normal road pavement structures and therefore the normal design procedures apply. These were developed by Weinert (1980) and based on three macro-climatic regions in South Africa based on the Weinert N-value, i.e. dry ($N \geq 5$), moderate ($5 > N \geq 2$) and wet ($N < 2$), that are of significance for road engineering. The South African National Roads Agency SOC Ltd (SANRAL) published the South African Pavement Manual in 2013 in which it states that the Thornthwaite's Moisture Index provides a more sensitive differentiation in climatic regions than the Weinert N-value with an interpretation into five climatic regions ranging for arid to humid.

The performance of hot mix asphalt surfacing layers are largely affected by the temperature conditions and Viljoen (2001) and Denne-man (2007a and b). Whereas this holds true for the design of asphalt pavements under normal traffic loading, it is especially important for the design of BRT pavements where the performance of hot mix asphalt surfacing layers is more critical in terms of resistance to permanent deformation because of the high wheel loads and channelized traffic (refer Figure 1 discussed earlier). It is therefore recommended that pavement designers carefully analyse expected surface temperature conditions of BRT pavements and accordingly select the most appropriate binder type for the proposed asphalt mix.

The performance of concrete pavements is affected by the daily temperature cycle, i.e. the difference between the daily maximum and



FIGURE 3 My CiTi BRT system. Standard bus

Articulated bus

Mini bus

minimum temperatures. This parameter is therefore one of the input parameters for the design of concrete pavements and needs to be evaluated by the pavement designer prior to the design of BRT pavements.

BUS TRAFFIC LOADING

Types of buses

Broadly speaking there are three types of buses operating on BRT systems and IRPTN's. These are:

- Standard bus, approximately 12 m in length;
- Articulated bus, 16.5 – 18 m in length; and
- Feeder line mini bus, approximately 9 m in length.

Illustrations of these bus types are shown in Figure 3 above. Usually articulated buses only operate on BRT trunk routes and mini buses only on complementary feeder routes in mixed traffic. The standard buses operate both on trunk and complementary routes.

Typical data and other specific data required for the design of BRT pavement structures is summarised in Table 1.

Mercedes and Marcopolo have in recent years launched their latest models in terms of high capacity buses. The CapaCity from Mercedes is 19.5 m in length and is capable of carrying up to 193 passengers (with a larger component of standing passengers for shorter urban trips), while the Macropolo Viale BRT bus (see Figure 4), specifically aimed at BRT systems, is 21 m in length and can accommodate up to 145 passengers (with a large component of seated passengers).

Tyre pressure and maximum wheel loads

A typical tyre used on buses is the 295/80R x 22.5 (see Figure 5). This tyre is fitted on bus rims that are 22.5" (572 mm) in diameter. The width

of the tyre is 303 mm and the recommended operating tyre pressure is 825 kPa. The tyre pressure is an important design parameter in pavement design as the contact stress on the pavement surface is assumed to be equal to the tyre pressure.

The maximum wheel load capacity of this tyre is 3.465 t when used in a single wheel configuration and 3.075t when used in a dual wheel configuration. It follows that, in terms of the maximum load rating of the tyres the maximum axle load on a single wheel configuration axle is 6.93 t and on a dual wheel configuration axle 12.3 t. It should be noted that in some instances the maximum tyre load rating could be limiting the total axle load, even though the axle may be designed for a slightly higher axle load rating.

Bus occupancy levels

Bus occupancy levels are critical in the determination of the traffic loading of BRT buses on the pavement. It can be seen in Table 1 that the axle loads of an empty bus is a maximum of 7.5t for the drive and trailer axles. Full buses, on the other hand, have axle loads in excess of the legal permissible axle loads on public roads in South Africa.

The evaluation of transport needs, in terms of daily commuter and passenger numbers, and the determination of matching BRT system and IRPTN capacity will dictate the required bus frequencies and bus types (standard or articulated buses on trunk routes). This forms part of transportation planning and the discussion thereof is outside the scope of this paper.

During the planning stage of a BRT system or IRPTN it is necessary to determine the financial viability of the capital investment in the new infrastructure. Positive rate of returns are at the basis of the economical decision to proceed with the infrastructure investments and high passenger volumes and transportation needs results in higher rates of

TABLE 1 Bus type data sheet

Description	Standard bus	Articulated bus	Mini bus
Typical chassis supplier	Volvo B7R or Scania F-type	Volvo B12M or Scania K-type	Optare
Typical coach supplier	Marcopolo	Marcopolo	Optare Solo
Total passenger capacity [pax]	75	120	54
Seating capacity [pax]	45	55	33
Typical length [m]	12.0	16.5 – 18.0	9.0
GVM [t]	19.5	30.0	11.3
No. of axles	2	3	2
Drive axle configuration	single, dual wheel	single, dual wheel	single, dual wheel
Trailer axle configuration	n/a	single, dual wheel	n/a
Steering axle load (max/empty) [t]	7.1 / 3.0	7.5 / 3.0	3.8 / 2.4
Drive axle load (max/empty) [t]	12.0 / 7.5	12.0 / 7.5	8.0 / 2.2
Trailer axle load (max/empty) [t]	n/a	10.5 / 7.5	n/a
Tyres	295/80R x 22.5	295/80R x 22.5	215/75R x 17.5



FIGURE 4 Macropolo Viale BRT bus

return. Therefore, at the planning stage high passenger volumes benefit the economic viability of the BRT and IRPTN projects. During the design and construction stage on the other hand, high bus frequency and occupancy levels result in a higher cost of required infrastructure and particularly the cost of the pavement structure. This in turn reduces the economic viability of the projects. It is therefore important that at an early stage of the project, i.e. the planning stage, the transportation planners and the design engineers work closely together to arrive at the optimum balance of system capacity.

It is important to note that one cannot assume that all buses that operate on the system network are always 100% full. From experience, the author concludes that there is a tendency to ignore or to overestimate bus occupancy levels. This has a significant effect on the total estimated traffic loading on BRT pavements. For example, on a typical radial BRT trunk route in a South African situation between a CBD area and an outer-lying residential area buses would be operating close to full capacity during the morning peak in the direction of the CBD, but close to empty capacity in the opposite direction outer-lying residential areas. The

FIGURE 5
295/80R x
22.5



opposite holds true during the afternoon peak. Therefore, while the number of buses travelling in each direction may be similar on a radial trunk route, the occupancy levels and the resulting traffic loading on the BRT pavements differs significantly.

Information on the expected bus occupancy levels is normally not provided in great detail during the planning stage and it is therefore necessary for the pavement designer to make certain assumptions on occupancy levels per direction during the morning peak, the off-peak periods and the afternoon peak. The effect hereof is discussed in the following axle load equivalency factor section.

Standard axle load equivalency factor

It is preferred to undertake mechanistic pavement design using the actual axle load spectrum expected on the BRT pavements. Various pavement design software packages have this functionality, e.g. cncPave developed by the Concrete Institute. In the absence of such functionality the actual axle loads of the buses can be converted to an equivalent number of 80 kN standard axle loads (ESAL) per bus by determining the load equivalency factor per axle using Equation 1 in accordance with draft TRH4 1996 (Department of Transport, 1996) and subsequently determining the aggregate of the equivalency factors of all axles of the bus.

In order to determine the load equivalency factor per axle, the axle loads at the various bus occupancy levels need to be determined first. This information is often not readily available pending decisions with regard to procurement of the buses and coaches. Typical axle loads at varying occupancy levels are provided in Table 2 and should be used as a guideline.

Using the axle loads as shown in Table 2 and Equation 1 the number of ESALs per bus can be determined and these are summarised in Table 3.

It is noted a relative damage exponent of 4.0 is used to determine the ESALs. This is a generally accepted value for flexible pavements. For concrete pavement a higher relative damage factor of up to 5.0 is often used. In the worst case scenario this would result in 11.6 ESALs per 100% full articulated bus and 7.5 ESALs for a 100% full standard bus (on concrete pavements).

From the above table it can be seen that there is a significant difference in the contribution of full vs partially full or empty buses in terms of the traffic loading on BRT pavements. The cumulative effect on the total traffic loading over a 30 year structural design period for BRT pavements is very significant.

As an example to illustrate the above, on a certain section of the Ekurhuleni IRPTN trunk route between Tembisa and Kempton Park the expected number of articulated buses is approximately 259 per day plus an additional 33 standard buses. The cumulative traffic loading over a 30 year design period was determined by the pavement design engineers to be 21 million ESALs, assuming that 25% of all buses will be 100% full, 50% of all buses half-full and the remaining 25% nearly empty (25% full). In the case that all buses would be 100% full at all times, the cumulative traffic loading over 30 years would increase by 70% to 36 million ESALs.

In this regard it should be noted that a bus is only 100% full if all seats are taken and all remaining standing space in the aisle is also fully occupied. From Table 1 it can be seen that even when all seats on an articulated bus are taken (and the bus looks full because there are no more available seats) the bus is only filled to 45% of its capacity.

TABLE 2 Axle loads (steering / drive / trailer)

Description	Standard bus	Articulated bus	Mini bus
Max GVM [t]	19.5	30.0	11.3
Max payload [t]	9.0	12.0	6.7
100% full	7.5 / 12.0 / -	7.0 / 11.5 / 11.5	3.4 / 7.9 / -
75% full	6.4 / 10.9 / -	6.0 / 10.5 / 10.5	3.2 / 6.5 / -
50% full	5.3 / 9.8 / -	5.0 / 9.5 / 9.5	2.9 / 5.0 / -
25% full	3.6 / 9.2 / -	4.0 / 8.5 / 8.5	2.7 / 3.6 / -
empty	3.0 / 7.5 / -	3.0 / 7.5 / 7.5	2.4 / 2.2 / -

Description	Standard bus	Articulated bus	Mini bus
100% full	5.4	8.5	0.9
75% full	3.5	5.8	0.4
50% full	2.2	3.8	0.16
25% full	1.7	2.4	0.05
empty	0.7	1.5	0.01

TABLE 3 No. of equivalent 80 kN single axle loads (ESAL) per bus

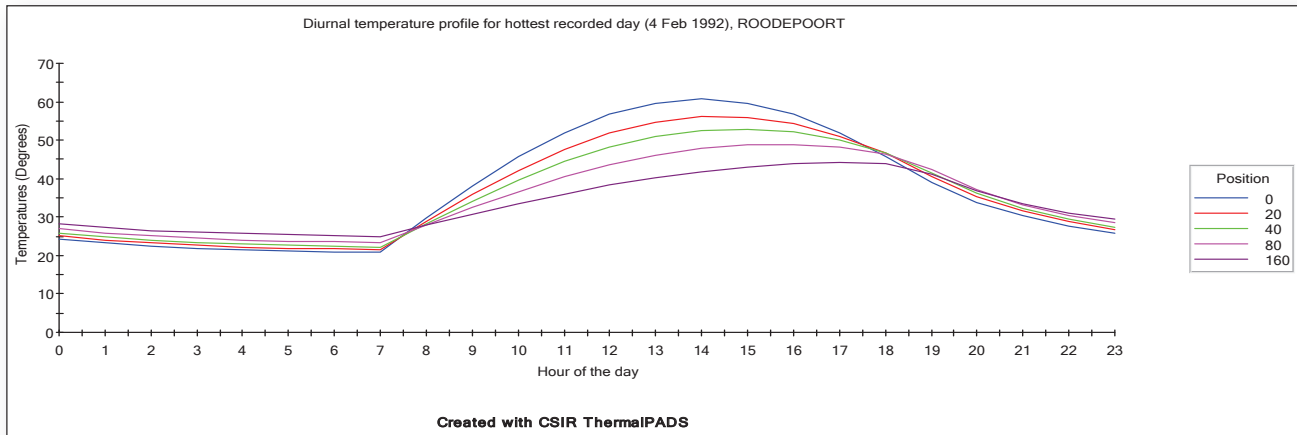


FIGURE 6 Graphical presentation of estimated daily pavement temperature fluctuations at different depths below the surface.

BRT PAVEMENT DESIGNS

The author has since 2008 been involved in developing BRT pavement designs for the Johannesburg Rea Vaya, the Rustenburg Yarona, the eThekweni Go!Durban and the Ekurhuleni Harambee. These include both flexible pavements (asphalt with and without binder modification) and rigid pavements (continuously reinforced concrete pavements). These designs are briefly discussed in the following sections to provide the reader with an overview of typical BRT pavements designs in relation to total daily bus volumes, type of buses, and the estimated number of total cumulative ESALs.

Johannesburg Rea Vaya

Part of the City of Johannesburg's Rea Vaya BRT System was the up-grading, Portland Perth to Jan Smuts Avenue to provide new bus lanes on Section 5 of Phase 1A, which took place between 2007 and 2010. The work in this section entailed the widening of approximately 5.5km of the existing dual carriageway road to accommodate the new BRT lanes and BRT stations located in the median area.

It was estimated that a total of 107 standard buses and 103 articulated buses would be travelling on this section daily in each direction (with a headway of 2 minutes during the peak periods). At the time the number of ESALs per bus was determined to be 11.8 for the articulated buses and 8.7 for the standard buses. In hindsight, comparing these values with the values provided in Table 3, this was a conservative determination. The structural design period for this section was 20 years and the estimated cumulative traffic loading over this period was between 18 and 20 million ESALs.

A mechanistic pavement design procedure was carried out and the following pavement structure was recommended for the new BRT lanes:

- 40 mm bitumen-rubber continuously graded asphalt surfacing
- 125 mm asphalt base with a modified binder
- 150 mm C3 cement stabilized upper subbase
- 150 mm C4 cement stabilized lower subbase
- 150 mm G7 selected subgrade layer
- In situ G7 roadbed material

The operating temperatures for the new pavement were evaluated using the "Thermalpads" programme, which indicated that temperatures as high as 60°C at the surface to 50°C at the bottom of the asphalt surfacing layer could be expected. This is illustrated in Figure 6.

It was expected that a standard bitumen binder would not perform satisfactorily at these prevailing asphalt temperatures and therefore a

bitumen-rubber modified bitumen binder was recommended for the surfacing and an A-E1 or A-P1 modified binder for the asphalt base.

Rustenburg Yarona

The first section of the Rustenburg Yarona IRPTN that was constructed was the Fast Track Section 01 of Contract A from km 10+500 up to km 15+250 along Swartruggens Road (R104 / P2-3). Construction took place between 2012 and 2014.

The average daily bus numbers provided by the planners were 384 standard buses and 213 articulated buses. Of these it was assumed that 260 standard buses and 145 articulated buses would be 75% full to full, with the remainder divided into 50% to 75% full and 25% to 50% full categories. At the time the number of ESALs per bus was determined to be 10.9 for a full articulated bus and 5.1 for a full standard bus. The structural design period for this section was 30 years and the estimated cumulative traffic loading over this period was approximately 23 million ESALs.

Due to the 30 years structural design period, the high expected pavement temperatures in the Rustenburg area and the maximum axle loads expected to be as high as 12.2t a concrete pavement was preferred. The cncPave software package was used to design a continuously reinforced concrete pavement (CRCP) for the BRT lanes as follows:

- 220 mm CRCP (4.2 MPa flexural strength) with Y16 high tensile reinforcing bars placed at 150mm centres
- 150 mm C3 cement stabilized upper subbase
- 150 mm C4 cement stabilized lower subbase
- 150 mm G7 selected subgrade layer
- In situ roadbed material

eThekweni Go!Durban

The Go!Durban IRPTN in eThekweni involves inter alia the design and construction of a network of BRT routes. This section deals with BRT Line C1A, which runs on the northern side of the Umgeni River from the intersection of Inanda Road and Dumisani Makhaye Drive (previously MR577) at SV 7+700 to Sea Cow Lake Road (formerly Old North Coast Road) at SV 16+200, a distance of 8.5 km.

Detailed information on the type of buses and the estimated number of buses on the BRT route was determined during the preliminary design phase by other consultants. An articulated bus with a 7.2t steering axle, 10.0t drive axle and 13.0t trailer axle was specified for a fully loaded condition. A 30 year design period was specified with a 15 year initial development period of 4.5% annual growth in bus traffic and the 15 year full demand period. During the latter period a one minute headway was estimated during the peak periods and a five minute headway during off-peak periods, resulting in a total of 480 articulated buses per day. An assumption was made that per day 75% of the buses would be full and 25% half-full. The number of ESALs per bus was determined to be 10.1 for a full articulated

bus and 5.3 for a half-full articulated bus. The estimated cumulative traffic loading over the 30 design period was estimated to be approximately 40 million ESALs. The design for this section of the Go!Durban IRPTN was recently completed and construction has not yet commenced.

Both rigid and flexible pavement design options were considered. While due to the high number of cumulative traffic loading a rigid pavement would be a good alternative, the client for various reasons favoured a flexible pavement design option incorporating a high modulus asphalt base using an EME asphalt (Enrobé à Module Élevé, which is French for mix with a high modulus).

The flexible pavement design option was analysed using the Rubicon Toolbox software. A stiffness modulus of 9000 MPa was used for the high modulus asphalt base in these analyses, which was considered to be conservative as a modulus of at least 14000 MPa is stated by the South African Bitumen Association (SABITA, 2013) in its Manual 33 "Interim Design Procedure for High Modulus asphalt Mixes". The chosen stiffness modulus of 9000 MPa is significantly higher than a generally accepted stiffness modulus of 5000 MPa for a normal asphalt base and because of this a considerable reduction in thickness design of the asphalt base can be achieved. The recommended pavement structure for the new BRT lanes was as follows:

- 40 mm asphalt surfacing
- 125 mm high modulus asphalt base (min 9000 MPa)
- 300 mm C3 cement stabilized subbase
- 150 mm G7 upper selected subgrade layer
- 150 mm G9 lower selected subgrade layer
- In situ G10 roadbed material

Ekurhuleni Harambee

Following an earlier planning phase, the Ekurhuleni Metropolitan Municipality commenced in 2013 with the design of the Phase 1A of the Harambee IRPTN North / South Corridor. Phase 1A stretches from Tembisa in the north to OR Tambo International Airport in the south with a total length of approximately 16 km. Phase 1A is divided into 7 areas and this section deals with the pavement design for Area 2 and 3A, which is a section of trunk route along Andrew Mapheto Drive carrying the highest bus traffic loading. The design of this section was completed in 2014 and construction is well underway (to be completed by the end of 2016).

A daily total of 259 articulated buses and 33 standard buses was estimated per day per direction based on a 2 minute headway during peak periods and a 12 minute headway during off-peak periods. The number of ESALs per bus was determined to be 8.0 for a full articulated bus and 5.0 for a full standard bus. It is noted that these values compare well with the values as per Table 3. An assumption was made that of all buses 25% would be full, 50% half-full and 25% nearly empty (25% full). For the structural design period of 30 years the total cumulative traffic loading was estimated at 21 million ESALs.

Based on favourable price comparison between the rigid pavement design option and the flexible pavement design option (this price information was available from as-and-when construction tenders that were called for prior to the completion of the final designs) the following rigid pavement design option was selected (this is a similar pavement design to the one discussed above for Yarona):

- 220 mm CRCP (4.2 MPa flexural strength) reinforced with Y16 high tensile reinforcing bars placed at 150mm centres
- 150 mm C3 upper stabilised sub-base layer compacted to 97% of modified AASHTO density
- 150 mm C4 lower stabilised sub-base layer compacted to 95% of modified AASHTO density
- 150 mm G7 quality selected subgrade layer compacted to 93% of modified AASHTO density

In situ subgrade compacted to 93% of modified AASHTO density

The rigid pavement design option was developed using cncPAVE5 V0.4 programme. With the best subbase support achievable, within practical and economic considerations, the concrete thickness and reinforcement quantity were determined. This took place in various iterations to ensure that the desirable crack spacing is obtained and that the future maintenance costs are kept well within acceptable limits. The two main parameters of continuously reinforced concrete pavement used for design purposes are the crack spacing (X, m) and the percentage of shattered concrete (SH %) at the end of the design life. An example of the cncPave design outputs for the concrete pavement design option is shown in Figure 7.

It can be seen that the crack spacing to be expected is in the order of 1.7 – 1.8 m. For good structural performance the desirable crack spacing is between 1.5 m and 2.0 m. Therefore, in terms of expected crack spacing the proposed pavement design is satisfactory. The percentage of concrete that is expected to be shattered at the end of the structural design period, i.e. 30 years, is between 0.40% and 0.45%. It is noted that the range of 0.2 – 0.5 % is deemed to be acceptable, with shattered areas of more than 0.5 % being deemed excessive. Therefore, also in terms of shattered concrete the proposed pavement design is satisfactory.

PRACTICAL CONSIDERATIONS AND LIMITATIONS

Rigid (concrete) pavement vs flexible (asphalt) pavement

Concrete pavements generally have a longer structural design life with less maintenance required during the in-service life. The ultimate load carrying capacity of concrete pavements is also higher than that of asphalt pavements. BRT pavements are generally designed for 30 years and carry high volumes of heavy bus traffic and therefore concrete pavements are ideally suited for BRT lanes.

Concrete pavements, however, are more expensive to construct initially. Concrete pavements require longer construction period and are ideally constructed in longer uninterrupted sections. Long and straight sections of BRT lanes, typically on BRT trunk routes radiating out of a CBD area, are therefore ideal for concrete pavements.

Flexible pavement design options, on the other hand, require significantly less construction time and are easier to construct, particularly in busy CBD areas with many curves and corners, restricted working space and more stringent traffic accommodation requirements. Flexible pavements are also preferred in CBD areas in terms of future geometric improvements and when required are generally easier to repair.

There is, however, no fixed decision-based model that one can apply to the choice between concrete and asphalt pavements for BRT lanes. Instead each project case needs to be evaluated on its own merits and with its own weighting assigned to the various decision criteria. It should be noted, however, that the final choice is not necessarily for the option with the lowest cost or the highest structural capacity, but often a trade-off between economic, structural, practical and constructability considerations.

BRT pavements at bus stations

Particularly at the bus stations, where the BRT buses dock at the station platforms, the wheel loading is extremely channelized and slow moving. Under slow moving traffic the resilient response of asphalt is much lower than under high speed movement, making the asphalt more susceptible to permanent deformation. This in combination with the high shear forces exerted on the surfacing by the breaking and accelerating movements of the buses requires that specific attention be given to the design of the surfacing layer at stations.

A concrete pavement is ideally suited to withstand the slow moving channelized heavy wheel loads and the shear forces. The concrete pavement could either be a short section of CRCP (in case the remainder of the

BRT lane is not constructed with a CRCP) or jointed concrete pavement (JCP). The advantage of JCP is that it is easier to construct over a short section, but the disadvantage is that the joints reduce the riding quality and require more maintenance, specifically during the latter part of the service life.

It is not recommended to construct a normal asphalt wearing course at bus stations. Even with binder modification, the satisfactory performance of an asphalt surfacing at bus stations is not guaranteed. A possible hybrid of asphalt and concrete is a 40 mm open graded asphalt (void content 20 – 25%) of which the voids are filled with a resin-modified cement grout. This provides a durable and rigid surfacing at the bus stations that is able to withstand high shear forces and slow moving wheel loads. This type of surfacing was successfully applied at bus stations on the section of the Johannesburg Rea Vaya discussed above and is performing satisfactory.

BRT pavements at intersections

Traffic accommodation at intersections can be a major cause of disruptions at larger intersections in an urban environment. The time required to construct a concrete BRT pavement through an intersection is significantly longer than for asphalt pavements and would require the median part of the intersections to be closed for a number of weeks. This may prove to be extremely impractical, if not impossible. As an alternative to concrete pavements, it is recommended that flexible pavements with thick asphalt bases be considered at intersections in lieu of concrete pavements.

In the Cape Town CBD the intersections of the MyCiti system were constructed with 270 mm asphalt base with A-P1 binder modification, placed in three lifts of 90 mm each, and a 40 mm asphalt wearing course with A-E2 binder modification. On the section of the Harambee in Ekurhuleni discussed above the CRCP BRT lanes were discontinued at intersections and replaced with a thick asphalt base (with 35/50 penetration grade bitumen) and a 40 mm asphalt wearing course with A-E2 modified binder. These types of pavement structures can be constructed over two weekends, i.e. one weekend for the asphalt base and one weekend for the asphalt surfacing, with trafficking over the completed base during the interim period.

CONCLUSIONS

This paper provides a brief historic background to BRT systems. An exponential increase in total BRT system length was observed after 2000. In South Africa the first BRT systems and IRPTN's became operational in Cape Town and Johannesburg shortly before the 2010 Soccer World Cup, while currently BRT systems and IRPTN are being rolled out in at least 13 cities and metropolitan areas in South Africa.

Typical axle loads at varying occupancy levels for standard buses, articulated buses and feeder buses and the associated number of equivalent standard axle loads per bus are provided in this paper, which can be used as a guideline by pavement designers. It is concluded that there is a tendency to ignore or to overestimate bus occupancy levels. While the number of buses travelling in each direction on a radial trunk route may be similar, the occupancy levels during morning and afternoon peak periods and the resulting traffic loading on the BRT pavements differs significantly.

If this is not taken into account, it has a significant effect on the total estimated traffic loading on BRT pavements. It is therefore important that at an early stage of the project, i.e. the planning stage, the transportation planners and the design engineers work closely together to arrive at the optimum balance of system capacity.

Pavement designs developed for four major BRT systems in South Africa are discussed in this paper. These include concrete pavements, asphalt pavements and the use of high modulus asphalt. Details

with regard to bus occupancy levels and bus equivalency factors adopted in these designs are provided, as well as the cumulative traffic loading, which ranges from 18 to 40 million ESALs. This information can be used by pavement designers as a reference for other BRT pavement designs.

With regard to pavement design for BRT lanes, pavement designers need to carefully consider that the performance of hot mix asphalt surfacing layers is significantly affected by the temperature conditions. Especially for the design of BRT pavements it is important to carefully evaluate expected pavement temperatures and to select appropriate binders to provide sufficient resistance to permanent deformation under the high wheel loads and channelized traffic.

It should furthermore be noted that there is no fixed decision-based model that one can apply to the choice between concrete and asphalt pavements for BRT lanes and each project case needs to be evaluated on its own merits and with its own weighting assigned to the various decision criteria.

Pavement designers should also give specific attention to the design of the surfacing layer at bus stations. A concrete pavement is ideally suited to withstand the slow moving channelized heavy wheel loads and the shear forces at stations, but an open graded asphalt filled with a resin-modified cement grout provides a good alternative.

Practical considerations may also influence the choice of pavement type. E.g. traffic accommodation at intersections in CDB areas can be a major cause of disruptions and it is recommended that flexible pavements with thick asphalt bases be considered at intersections in lieu of concrete pavements due to the significantly short construction period which typically can take place over two weekends.

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