Gautrain tunnels: surface vibration and ground-borne noise

by J.L. van Niekerk*, J.P.L. Morgan†, and D. Cosijn‡

Synopsis

The proposed Gautrain Rapid Rail Link (GRRL) will require approximately 15 km of double or twin high-speed rail track tunnels located for the greater part beneath the northern suburbs of Johannesburg, including Houghton, Rosebank and Sandton. During the Environmental Impact Assessment (EIA) it became clear that potential surface vibration above and in the vicinity of the tunnels was a matter of serious concern to the residents of the affected properties and that the impact required assessment. The general method proposed is based on a US Department of Transportation, 1998, publication in which a base vibration curve derived for typical high-speed passenger trains is adjusted for the topological, geological and other features to predict the surface vibration and the associated ground-borne noise. The predictions indicate that some isolated areas might be impacted but that the impact will likely be limited, and it is possible to mitigate the impact using suitable track construction methods and track support systems.

Introduction

The Gautrain Rapid Rail Link is planned to link Johannesburg (Park Station) to Pretoria, and terminate in the eastern suburbs of Pretoria at Hatfield. The route is virtually a direct line with stations planned at Park Station, Rosebank, Sandton, Marlboro, Midrand, Centurion, Pretoria Station and Hatfield. From Sandton a separate commuter and direct airport link service is planned to Rhodesfield (Kempton Park) and to the Johannesburg International Airport (JIA), terminating in an underground station located between Terminal A—the international terminal and Terminal C—the recently opened domestic terminal.

The Gautrain Provincial Government required that the trains be able to complete the journey between Johannesburg and Pretoria in 35 minutes or less and from Sandton to JIA in less than 15 minutes. To achieve this, train speeds of at least 160 km/h are required. An 180 km/h route alignment has been achieved, except for the section between Pretoria and Hatfield where the maximum speed will be approximately 120km/h. In keeping with modern international train design and to maximize the possibility of obtaining state-of-the-art trains at the lowest cost, a standard gauge (1 435 mm gauge) solution has been adopted utilizing electric multiple units, which have powered axles distributed along the full length of the train. To achieve the levels of acceleration required, it is expected that approximately 50% of the axles will be powered. This in turn permits the train to traverse gradients in excess of 5°, which is well in excess of the capabilities of conventional trains, the major limitation being power requirements to achieve the speeds required.

Even so, the topography along the route requires that tunnels be provided between Johannesburg and Sandton. To achieve a cost-effective solution, it was also necessary to continue the tunnel from Sandton to Marlboro where the alignment daylights for the first time. At the entrance to Pretoria, the route is tunnelled beneath Salvokop and passes beneath the existing station, roughly at right angles. Underground stations are provided at Rosebank, Sandton (approximately 35 m below Rivonia Road) and at JIA.

Methodology

There are no South African regulations at present for railway generated noise or vibration emissions. A literature search also revealed very few standards for the limitation of railway generated vibration emissions.

Although there are various methods used to predict the vibration levels due to

* *Department of Mechanical Engineering, Stellenbosch University.*

† *R&H Railway Consultants (Pty) Ltd.*

‡ *Jongens Keet Associates*

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underground rail systems, very extensive measured data are usually required. In the case of the GRRL project, only a very general idea of the train type to be provided existed at the time the EIA assessment was undertaken. This, together with the relatively great length of the tunnel, combined with the very preliminary stage of the geotechnical investigations, which would gradually be added to during the EIA process, indicated that a more generalized approach would have to be taken.

The US DOT document entitled 'Transit Noise and Vibration Impact Assessment', 1995[1] contains such a generalized approach. This document was supplemented by a later document that was based on the 1995 document but extended to cater for high-speed trains–High-Speed Ground Transportation Noise and Vibration Impact Assessment, 1998[2]. The procedures and methods outlined in this later document were used to predict the vibration levels when carrying out the preliminary vibration assessment.

A preliminary vibration assessment as defined in[2] has three levels of detail for predicting ground-borne vibration and re-radiated noise:

- *Screening*—uses a table of distances to determine likely areas of impact. For speeds of up to 160 km/h this extends up to 40 m to 60 m from the track centre-line.
- *General Assessment*—uses generalized data to develop a curve of vibration level as a function of distance from track. These data are based on the high range for 'normal' geology. The actual values can be 5 dB(V) or lower, in general.
  Note:
  When used to describe vibration, a decibel scale is often used. The vibration level, the number of decibels (dB(V) in metric terms) is 20 times the logarithm (to the base 10) of the ratio (v/v_{ref}), where v is the root mean square (RMS) of the velocity amplitude and v_{ref} is a reference RMS velocity amplitude.
  Because the net average of a vibration signal is zero, the root mean square (RMS) amplitude of the velocity is used to describe the 'smoothed' vibration amplitude. It is the average of the squared amplitude of the vibration velocity.
  In metric terms, the ISO reference velocity amplitude is 1×10^{-9} m/s and the abbreviation dB(V) is used. There is another reference velocity used sometimes when working in the metric system and it is 5×10^{-8} m/s, which appears to be used mainly in the United Kingdom. In the USA the accepted reference amplitude is 1×10^{-6} in./s and the abbreviation VdB is used to differentiate the different reference velocity amplitudes.
- *Detailed Analysis*—usually performed during the final design phase where there is sufficient reason to suspect adverse vibration impact.

All references to the vibration levels that follow are in dB(V) and are based on a reference velocity level of 1×10^{-9} m/s.

The general assessment begins by using a base curve (See Figure 1), which represents an upper-bound for typical high-speed train ground vibration measurements. The base curve published in the report[2] was based on a speed of 150 mph (240 km/h). The design speed chosen for the GRRL is 180 km/h and is shown in Figure 1.

As the vibration travels through the ground it steadily reduces as the distance increases. It can be seen that at about 10 m from the track, it has reduced by about -6 dB(V), by about -13 dB(V) at 25 m and by about -28 dB(V) at 100 m, all for normal geological conditions.

The use of high resilience fastenings between the rail and the track slab will attenuate (mitigate) vibration by about -5 dB(V) to -10dB(V), depending upon the complexity (and cost!) of the fastening used. Where conditions require an even higher attenuation to meet design requirements, the use of a floating track slab will attenuate the vibration by about -15 dB(V). For purposes of the general assessment that follows, no mitigation was assumed.

The vibration in the ground has then to penetrate the building, with appropriate coupling losses. These vary from –7 dB(V) for a 1–2-storey brick building to –13 dB(V) for a large masonry building on spread footings.

Dealing with variable geological conditions and features at a general assessment level can never be an exact science. In practice, a variation of 5 to 10 dB(V) can be found under apparently similar conditions. Hence the use of generalized data based on the high range for 'normal' geology when carrying out a general assessment. The actual figures can be 5 dB(V) or more lower.

The adjustment factors to detailed above are from[2] and are shown in Table I.

Train Speed: The source vibration level depends on the train speed. The vibration velocity level L_v varies as follows:

$$\Delta_{L_v} = 20\log\left(\frac{speed}{speed_{ref}}\right) dB(V)$$

From a scan of potential trains available, it was expected that the power to weight ratio of a typical train would be of the order of 9.7 kW/t (350 kW net per 18 t axle at a motorization ratio of 50%). Simulations performed from first principles indicated that such a train could complete the journey in the required minimum time without exceeding a speed of 160 km/h, which is the lowest maximum service speed requested of the bidders.

In tunnels, the minimum achievable speed required is reduced to 140 km/h to permit a smaller tunnel cross-sectional area while retaining passenger comfort criteria due to aerodynamic effects.

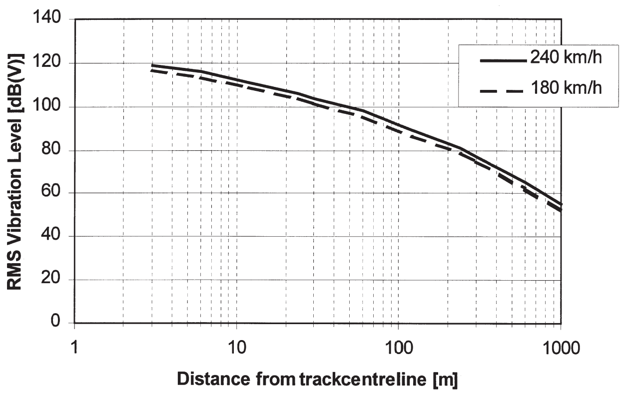

Figure 1—Vibration levels at various distances from the centreline of the track used as the input vibration (adapted from[2])

Table I

Adjustment factors for generalized predictions of ground-borne vibration and noise (from Table 8.2 in[2])

Factors affecting vibration source		
Source factor	**Adjustment to propagation curve**	**Comment**
Speed	Vehicle speed — Adjustment (Ref Speed = 150 mph) 300 mph — +6.0 dB 200 mph — 2.5 dB 150 mph — 0.0 dB 100 mph — -3.5 dB 75 mph — -6.0 dB	Vibration level is approximately proportional to 20*log (speed/speed$_{ref}$). Sometimes the variation with speed has been observed to be as low as 10 to 15 log (speed/speed$_{ref}$)
Resilient wheels	0 dB	Resilient wheels do not generally affect ground-borne vibration except at frequencies greater than about 80 Hz
Worn wheels or wheels with flats	+10 dB	Wheel flats or wheels that are unevenly worn can cause high vibration levels. This problem can be prevented with wheel truing and slip-slide detectors to prevent the wheels from sliding on the track
Worn or corrugated track	+10 dB	If both the wheels and the track are worn, only one adjustment should be used. Corrugated track is a common problem; however, it is difficult to predict the conditions that cause corrugations to occur. Rail grinding can remove rail corrugations
Crossovers and other special trackwork	+10 dB	Wheel impacts at special trackwork with standard frogs will significantly increase vibration levels. The increase will be less at greater distances from the track. Moveable point frogs mitigate this problem
Floating slab trackbed	Select highest one that applies: -15dB	The reduction achieved with a floating slag trackbed is strongly dependent on the frequency characteristics of the vibration
Ballast mats	-10 dB	Actual reduction is strongly dependent on frequency of vibration
High resilience fasteners	-5 dB	Slab track with track fasteners that are very compliant in the vertical direction can reduce vibration at frequencies greater than 40 Hz
High resilience fasteners		
Resiliently supported ties	-10 dB	Resiliently supported tie systems in tunnel have been found to provide very effective control of low-frequency vibration
Type of track structure	Relative to at-grade ties and ballast: Aeriel/viaduct structure — -10 dB Open cut — 0 dB Relative to bored tunnel in soil: Station — -5 dB Cut and cover — -3 dB Rock-based — - 15 dB	The general rule is: the heavier the structure, the lower the vibration levels. Putting the track in cut may reduce the vibration levels slightly. Rock-based tunnels will shift vibration to a higher frequency
Factors affecting virbration path		
Path factor	**Adjustment to propagation curve**	**Comment**
Geologic conditions that promote efficient vibration	Efficient propagation in soil — +10 dB	Refer to the text for guidance on identifying areas where efficient propagation is possible
Propagation	Propagation in rock layer — **Dist.** / **Adjust** 50 ft — +2 dB 100 ft — +4 dB 150 ft — +6 dB 200 ft — +9 dB	The positive adjustment accounts for the lower attenuation of vibration in rock compared to soil. Because it is more difficult to get vibration energy into rock, propagation through rock usually result in lower vibration than propagation through soil
Coupling to building foundation	Woodframe — -5 dB 1–2 Storey commercial — -7 dB 2–4 Storey masonry — -10 dB Large masonry on piles — -10 dB Large masonry on spreading footings — -13 dB Foundation in rock — 0 dB	The general rule is: the heavier the building construction, the greater the coupling loss
Factors affecting virbration receiver		
Receiver factor	**Adjustment to propagation curve**	**Comment**
Floor-to-floor attenuation	1 to 5 floors above grade — -2 dB/floor 5 to 10 floors above grade — -1 dB/floor	This factor accounts for dispersion and attenuation of the vibration energy as it propagates through a building
Amplification due to resonances of floors, walls, and ceilings	+6 dB	The actual amplification will vary greatly depending on the type of construction. The amplification is lower near the wall-floor and wall-ceiling intersections
Factors affecting ground-borne noise		
Rceiver factor	**Adjustment to propagation curve**	**Comment**
Radiated sound	Peak frequency of ground vibration: Low frequency (<30Hz) — -50 dB Typical (peak 30 to 60Hz) — -35 dB High frequency (>60Hz) — -20 dB	Use these adjustments to estimate the A-weighted sound level given the average vibration velocity level of the room surfaces. See text for guidelines for selecting low-, typical-, or high-frequency characteristics. Use the high-frequency adjustment for subway tunnels in rock or if the dominant frequencies of the vibration spectrum are known to be 60 Hz or greater

The expected upper limit power to weight ratio was expected to be 13.9 kW/t and this figure was used to determine the train speeds every 200 m along the route, thus providing a conservative basis to the vibration assessment.

Construction and rolling stock: Modern railway track has continuously welded rails and the absence of rail joints reduces the creation of vibrations. Main line higher speed turnouts and crossovers used in the GRRL will have swing-noses, thus also eliminating the gap at the point of crossing. Wheel flats, caused by wheel skids, can cause a high level of vibration. As a result, the rolling stock will have anti-skid braking systems (ABS) and disc brakes.

Geological conditions: Where the tunnel is founded in competent rock, care must be taken to apply the appropriate correction factors as higher frequency vibration propagates efficiently in such cases. It is also known that a high water table assists the propagation of vibration, but no simple quantification of this phenomenon is available.

Ground-borne (or re-radiated) noise: Anecdotal evidence states that ground vibrations at the levels produced by underground rail traffic are almost never annoying. The major source of annoyance results from ground-borne noise. The vibration of, say, a wall, floor or ceiling, which will then act as a 'loudspeaker', is the most likely cause of annoyance.

Due to the relatively low frequency of the vibration and the fact that this noise cannot be reduced by 'closing a window', the permissible re-radiated noise level is set much lower than that for normal noise.

The A-weighted sound pressure levels were estimated using the values presented in Table I.

Assessment criteria

For this project, the guidelines in Annex A of ISO 2631-2[3] were used to derive a set of vibration levels that can be used to assess the impact of the predicted ground vibration levels. These levels are somewhat higher than those proposed in[2]. For instance, the recommended levels in the USA for residential buildings are 100 dB(V) and 108 dB(V) for frequent and infrequent events respectively. (The document does not differentiate between day-and night-time levels.) It is only for critical working areas where the USA levels are half those proposed in ISO 2631-2. It should, however, be pointed out that the levels referred to in ISO 2631-2 are for the averaged, weighted, RMS. velocity while the USA levels are for the un-weighted RMS. measurements. It is common practice to band limit the measured vibration signals between 1 and 80 Hz, for whole body vibration assessment, and in addition apply various frequency weighting curves, depending on the point where the vibration is entering the body as well as the direction. In general, the weighted levels will therefore be less than the unweighted levels.

The impact of low frequency noise was assessed according to the guidelines of[2], and the noise impact levels set therein were used for this project. These levels are in line with international practice[2], and are shown below in Table II.

To assess the relative permissible re-radiated noise levels with permissible normal 'open-air' noise levels, the maximum sound pressure levels in Table III are the land-related railway noise impact criteria, which may not be exceeded for the defined noise sensitive land uses along the project corridors, with the railway reserve boundary as reference control point.

These criteria are not specifically directly related to the train emission levels, as mitigating measures for the source noise emission levels may be taken in the intervening ground between the track and the reserve boundary.

Results and assessment

The predicted ground-borne noise and vibration results shown in Figure 2 are those pertaining to the tunnel section in Johannesburg. It is clear that for the sections of the track in tunnel, there will be no perceivable vibration present at the surface (approx. 90 dB(V)), except in one or two isolated areas. In the case where the track is on the surface, the vibration at the track centreline does exceed the impact levels, but 25 m away the levels have attenuated sufficiently to be below the impact criteria. It is therefore unlikely that the vibration from the passing trains will be noticed at the surface and hence no vibration impact is expected, except in some isolated areas.

However, low frequency noise due to ground-borne vibration may be audible in some areas above the tunnel sections, notably those areas where the bedrock is close to the surface. When the track is on the surface, the decay away from the centreline is similar to that for vibration, and again no impact is expected, except for some isolated areas.

Table II

Ground-borne vibration and noise level impact criteria

Period of day	Vibration level (Ref 1X10^{-9} m/s)	Noise level (re-radiated)
06h00–22h00 (daytime/evening)	112 dB(V)	40dB(A)
22h00–06h00 (night-time)	103 dB(V)	35 dB(A)
Critical working areas	100 dB(V)	30 dB(A)

Where critical working areas include:

- Hospital operating theatres (for vibration)
- Precision laboratories (for vibration)
- Auditoria (for noise)
- Concert halls (for noise)
- Theatres (for noise)
- Recording studios (including TV recording studios) (for vibratio and noise).

Table III

Noise level impact criteria

Period of day (T)	$L_{Aeq,T}$ (dB(A))	L_{Amax} (dB(A))
06h00 – 22h00 (daytime)	60	85
22h00 – 06h00 (night-time)	50	85

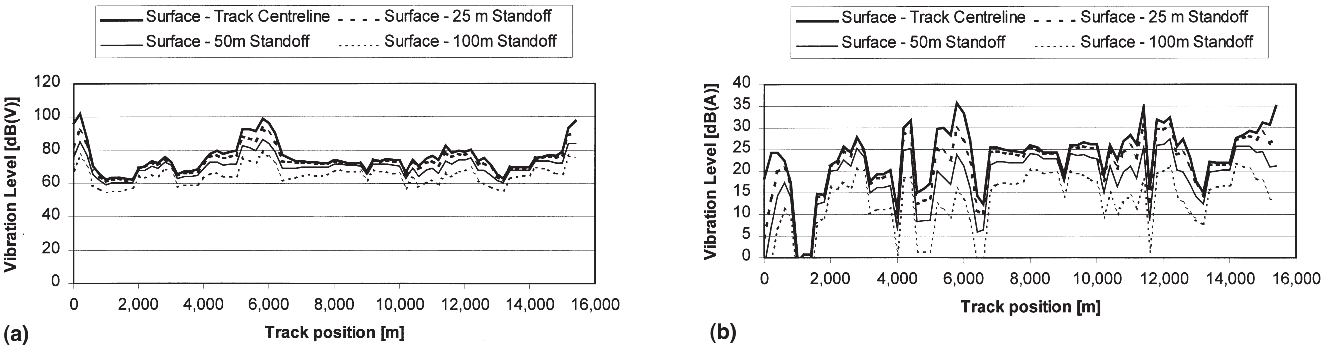

Figure 2— Predicted ground-borne vibration (a) and noise (b) levels—Johannesburg tunnel

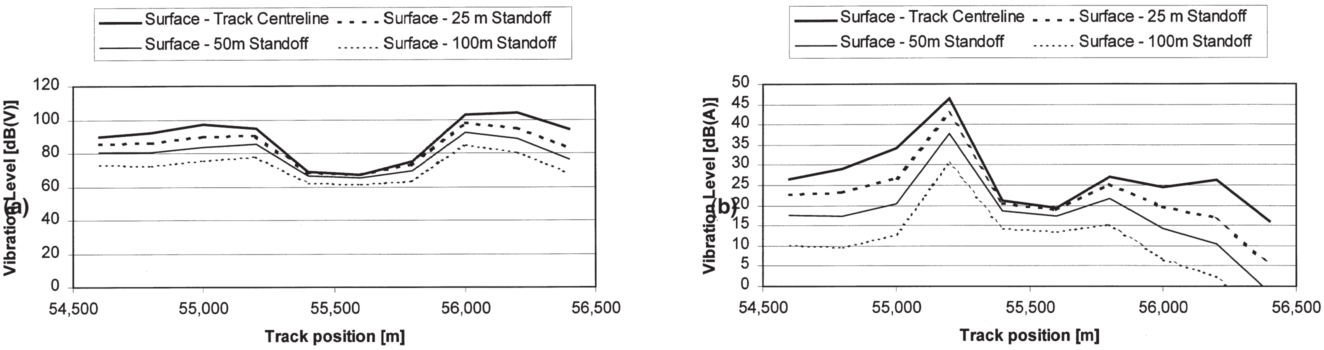

Figure 3—Predicted ground-borne vibration (a) and noise (b) levels—Pretoria Salvokop tunnel

Conclusion

Although the preliminary general assessment was carried out using typical railway vehicles and base vibration level curves, the results, which are also for unmitigated track forms and probably pessimistic rates of decay, indicate that that the surface vibration and ground-borne noise above the tunnels will cause no unacceptable impact, except in some isolated areas. Where such unacceptable impacts do occur, they can probably be successfully mitigated against by the appropriate choice of track forms.

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SA’s reputation for innovation in mining*

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The FutureMine research programme was run on a collaborative basis. ‘Industry partners that sponsored the programme steered the various research projects through the actions of expert committees, who were responsible for driving the research in specific technology areas. Eight different research areas were considered, addressing needs in: mineral resource management; access and ore reserve development; stoping technology; vertical and horizontal transport and logistics; worker and training issues; cooling and ventilation engineering; and information and communication technology in mining. The potential benefit or impact of a given technology or process was assessed by the expert group of the research area concerned, before moving forward.’

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