



**Vibration Assessment:**

**Waikato Expressway –  
Cambridge Section**



# Vibration Assessment:

## Waikato Expressway – Cambridge Section

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Date: 7-December-2010  
Reference: 2-61647.00 Task 963CL  
Status: Issue 3

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# 1 Introduction

This report presents the results of a desk study undertaken to calculate likely maximum ground vibrations arising from the construction and use of the 10.4 km long Cambridge Section of the NZ Transport Agency's (NZTA) Waikato Expressway, hereafter referred to as the Project. The objective of the study was to identify at an early stage potential adverse vibration effects so that appropriate mitigatory actions can be advanced.

The desk study involved the application of predictive models in conjunction with New Zealand specific inputs to estimate ground vibration from road construction activity and traffic and how these vibrations attenuate with distance. Typically, this approach produces conservative estimates of the maximum probable ground vibration. Therefore, the output from the desk study can be regarded as representing the upper bound of expected vibration levels.

The approach adopted for the Project to obtain estimates of ground vibrations has been successfully employed on a number of other high profile road construction projects including:

- The Christchurch Southern Motorway (NZTA)
- The Hawkes Bay Expressway – Southern Extension (NZTA)
- Te Awamutu Western Arterial (Waipa District Council)
- Acacia Bay Road Link (Taupo District Council)
- Rotorua Urban Transport Study (Rotorua District Council)

The Project is currently at the design stage and the proposed programme of works shows construction commencing in September 2012 and ending in May 2016. However, the 4 year construction period may be shortened through use of innovative construction techniques.

With reference to Figure 1, the majority of the Project is constructed through a greenfields route from State Highway 1 near Discombe Road to south of the Cambridge Golf Course. The Project will require construction of:

- 4 defined drain crossing points (including the Karapiro Stream Bridge crossing);
- 7 bridges;
- several hundred metres of retaining walls; and
- approximately 70 cross-highway culverts.

Key sensitive areas with regard to construction induced ground vibrations relate to the residential properties adjacent to the Expressway, particularly in the area from Watkins Road to the Karapiro Gully, and any construction traffic travelling along the residential corridor of Cambridge on SH1B (Victoria Road).

The principal construction activities will comprise:

- **Embankment Construction**  
This will require a significant volume of fill material to be carted to the construction site. Wherever possible, construction traffic will use the State highway network to minimise the use of local roads. Typical earthwork machinery will be used in the construction of the embankment, including bulldozers, motorscrapers and sheep-foot rollers for earthwork compaction.

- **Construction of Structures**

Seven bridge structures are proposed to be constructed along the corridor. It is envisaged that all of the bridges will be supported by driven piled foundations, except the Karapiro Viaduct Bridge, which will be constructed by bored concrete piles.

- **Pavement Construction**

Some form of flexible pavement system will be utilised. Therefore placement of the pavement will include compaction by vibratory roller.

Besides presenting the results of the desk studies, this report also considers:

- appropriate criteria for assessing the impact of construction works and construction traffic induced vibrations on buildings and their occupants;
- practical options for ensuring construction related vibrations are kept at acceptable levels; and
- ground vibrations generated by heavy commercial vehicles using the Expressway once it is open to traffic in relation to NZTA road roughness targets for Motorways/Expressways.

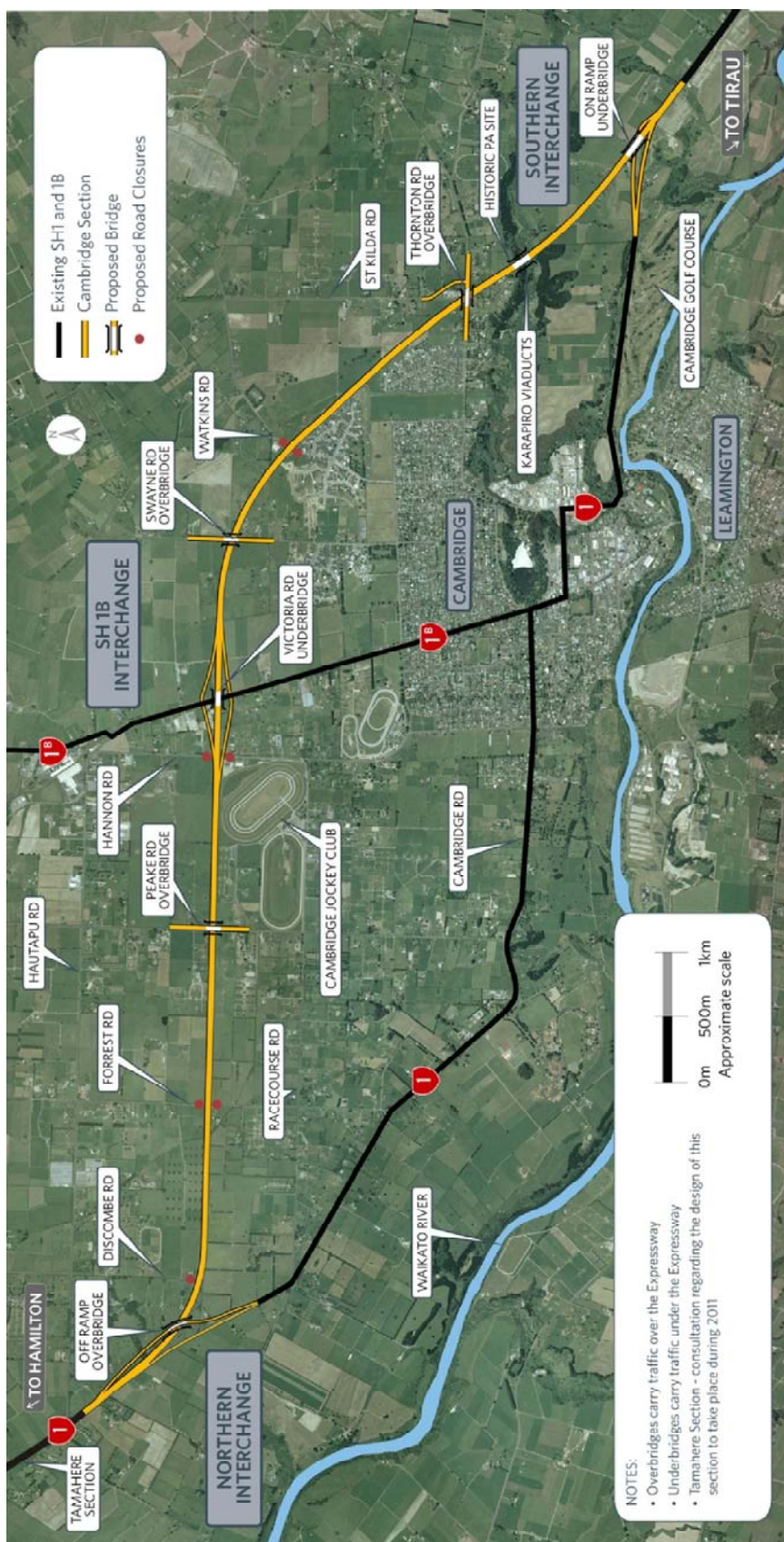


Figure 1: Spatial Schematic of Waikato Expressway, Cambridge Section

## 2 Methodology

The following steps have been performed in assessing construction and traffic induced vibrations generated by the Project.

1. Vibration levels at source are determined either from field measurements using accelerometers or from predictive models such as provided in British Standard BS 5228-2:2009 for mechanized construction works and Rudder (1978) for traffic.
2. An attenuation model that has been validated for New Zealand conditions is then applied to the source vibrations to generate plots of vibration level versus distance. The soil attenuation constants used with the model are chosen to be representative of the soil types present within and bordering the construction zone. These soil attenuation coefficients can be determined from published tables if the soil types are known or from in-situ measurements if not.
3. Guideline vibration levels for disturbance, complaint and structural damage drawn from current standards are next applied to the vibration attenuation plots to determine critical separation distances from the vibration sources.
4. Properties located within the separation distances are identified as being at risk from either construction activity or traffic and ameliorating measures considered appropriate are explored. In the case of construction vibration, this requires consideration of equipment location and processes.

Each of the above steps is expanded on in the following sections of the report.

### 3 Assessment Criteria

#### 3.1 Background

District Plans applying to the Project are those of Waikato District Council and Waipa District Council.

There are no specific vibration provisions related to construction and traffic in Waikato District Council's Operative District Plan. However, ground vibration is considered in Appendix I of the Proposed District Plan. The vibration conditions in Appendix I relate to blasting, which will not be employed on the Project. However, the following general guidance is provided in the Proposed Waikato District Plan with respect to human perception levels for ground vibration:

- *Vibration level less than 0.5 mm/s – imperceptible (threshold of perception)*
- *Vibration level of 0.5 mm/s to 2.0 mm/s – slightly perceptible (barely noticeable)*
- *Vibration level greater than 2.0 mm/s – distinctly perceptible (noticeable)*

*Vibration levels in excess of 5.0 mm/s have the potential to compromise amenity values.*

In contrast, both the Operative and Proposed Waipa District Plans contain the following specific provision:

*Vibration emanating from a site shall meet the limits recommended in and be measured and assessed in accordance with New Zealand Standard NZS 4403:1996 Code of Practice for Storage, Handling, and Use of Explosives (Explosives Code).*

The vibration damage criteria given in clause 10.5.5 of NZS4403:1996 are as follows:

- *For frequencies less than 3 Hz, the peak particle velocity should not exceed 50 mm/s.*
- *For frequencies between 3 and 20 Hz the product of peak particle velocity (V) in mm/s and the frequency (f) in Hertz should not exceed a constant K where  $K = 122$  i.e.  $Vf=K$ .*
- *For frequencies above 20 Hz, the peak particle velocity should not exceed 5 mm/s.*

The NZS4403 criteria are concerned with damage from ground vibrations generated by construction blasting in the vicinity of structures. Therefore, their application to vibration sources other than blasting is questionable.

Ideally, any standards - based criteria used to evaluate the significance of the calculated maximum probable ground vibrations in the vicinity of the Project should be as stringent as or more stringent than the guidance levels given in Appendix I of the Proposed Waikato District Plan and the Operative Waipa District Plan.

Vibration standards considered appropriate for the Project are discussed below. These standards state ground vibration in terms of peak particle velocity (ppv) with no requirement for frequency weightings, which simplifies their application to output from predictive models.

#### 3.2 Effect of Vibration on People

The vibration standard for human response that is traditionally applied in New Zealand and has been incorporated in a number of district plans is NZS/ISO 2631 (1989): "Evaluation of Human Exposure to Whole Body Vibration, Part 2: Continuous and Shock Induced Vibration in Buildings (1

to 80 Hz).” However this standard is no longer considered valid, as it was replaced in 2003 by an informative only standard containing no vibration criteria, and the Standards New Zealand’s adoption of the 1989 standard was withdrawn in 2005.

The current British Standard, BS 5528-2:2009 “Code of practice for noise and vibration control on construction and open sites - Part 2: Vibration” provides valuable information on people’s expectations and response to construction vibration in Annex B of the standard. This is reproduced in Table 1.

These guidance vibration levels are generally consistent with the recommendations of NZS/ISO 2631-2:1989 and are in terms of ppv, which is the vibration parameter routinely measured when assessing potential building damage. Therefore, the guidance vibration levels from BS 5528-2:2009 have been adopted to understand what the consequences of predicted construction related vibrations levels are likely to be in terms of human perception and disturbance.

In the case of nominally continuous sources of vibration such as traffic, vibration is perceptible at around 0.3 - 0.5mm/s ppv and above these values may become disturbing or annoying. However, higher levels of vibration are typically tolerated for single events or events of short duration occurring during the day-time. For example, blasting and piling are typically tolerated at vibration levels up to 12 mm/s ppv and 2.5 mm/s ppv respectively (NRA, 2004).

**Table 1: Guidance on effect of vibration levels (Table B.1 from BS 5228-2:2009)**

Vibration Level (ppv, mm/s)	Effect
0.14 mm/s	Vibration might be just perceptible in the most sensitive situations for most vibration frequencies associated with construction. At lower frequencies, people are less sensitive to vibration.
0.3 mm/s	Vibration might be just perceptible in residential environments.
1.0 mm/s	It is likely that vibration of this level in residential environments will cause complaint, but can be tolerated if prior warning and explanation has been given to residents.
10 mm/s	Vibration is likely to be intolerable for any more than a very brief exposure to this level.

### 3.3 Effect of Vibration on Structures

To assess the effect of ground vibrations on structures, the guidelines presented in the German Standard, DIN 4150-3 (1999): “Structural Vibration, Part 3: Effect of Vibration on Structures,” are considered appropriate. This standard has been widely used in New Zealand and has a history of successful implementation in projects that involve construction activities and/or blasting.

This DIN Standard provides guideline values which, when complied with, will not result in damage that will have an adverse effect on the structure’s serviceability.” For commercial, industrial and residential buildings, the DIN Standard considers serviceability to have been reduced if:

- cracks form in plastered surfaces of walls;
- existing cracks in the building are enlarged; and

- partitions become detached from loadbearing walls or floors.

The DIN standard deems these effects to be minor or superficial damage.

Table 2 summarises the vibration guidelines given in the DIN Standard.

With reference to Table 2, it will be noted that as the frequency of vibration increases, the level of vibration at which structural damage occurs also increases.

**Table 2: Vibration Guidelines from DIN 4150-3**

Type of Structure	Vibration Thresholds for Structural Damage (mm/s, ppv)			
	At Foundation			Uppermost Floor
	0 to 10 Hz	10 to 50 Hz	50 to 100 Hz	Frequency Mixture
Commercial /industrial	20	20 to 40	40 to 50	40
Residential	5	5 to 15	15 to 20	15
Sensitive/Historic	3	3 to 8	8 to 10	8

*Note: When a range of velocities is given, the limit increases linearly over the frequency range.*

### 3.4 Recommended Assessment Criteria

To identify roading projects that have the possibility of creating significant adverse vibration impacts, generalised data or predictive models are often used to provide estimates of ground vibration levels. Such general assessments deal with the overall vibration velocity and, unlike physical measurements, do not consider the frequency spectra of the vibration.

The criteria recommended for application to output from the vibration models used for assessing construction and traffic related ground vibrations from the Project are:

- 0.3 mm/s ppv for disturbance of building occupants (derived from BS 5228-2:2009); and
- 3 mm/s ppv for onset of building damage (derived from DIN 4150-3:1999).

With regard to the building damage criterion, the DIN Standard's more stringent limiting vibration level of 3 mm/s ppv applying to sensitive/historic buildings has been adopted instead of the 5 mm/s ppv applying to residential buildings. This has been done to provide a degree of conservatism and to account for the complex nature of soil characteristics, which introduces a degree of variability in how vibrations decay with distance.

The same criteria have recently been used to assess possible vibration effects caused by construction works and from construction traffic for the Greater Wellington Regional Council's (GWRC) Boulcott - Hutt Stopbank Project.

NZTA's Christchurch Southern Motorway and Hawkes Bay Expressway Projects also used essentially the same disturbance and damage criteria. However, because BS 5228-2:2009 had not been published at the time, a less stringent and only transport related disturbance criterion of 0.5 mm/s ppv derived from the Norwegian Standard NS 8176.E:2005 was employed.

## 4 Prediction of Peak Particle Velocity

Prediction of particle velocity of construction activities in soil involves the application of an attenuation relation. Attenuation describes the decay of peak velocity with distance from the vibration source. The attenuation relation is helpful in predicting velocities at variable distances from known velocities at a known distance.

For this study, the attenuation equation from Hiller and Crabb (2000), equation 1 below, was employed.

$$V_2 = V_1 \left( \frac{R_1}{R_2} \right)^{0.5} e^{-\alpha(R_2-R_1)} \dots (1)$$

where:  $V_1$  is the peak particle velocity at distance  $R_1$  (m),  
 $V_2$  is the peak particle velocity at distance  $R_2$  (m), and  
 $\alpha$  is the attenuation coefficient with the unit 1/m.

The attenuation coefficient is dependent on the frequency of the ground vibrations (Amick, 1999) as follows:

$$\alpha = \rho \pi f \dots (2)$$

where:  $\rho$  is a frequency independent material property of the soil (s/m),  
 $f$  is the dominant frequency of vibration.

Equation 1 addresses the two components of attenuation, geometrical spreading and material damping. In general, attenuation is greater at high frequencies (refer Equation 2) and for stiffer materials.

Attenuation measurements made on soils in the Waikato region suggest a suitable value for  $\rho$  is 0.0003 s/m.

Equations 1 and 2 were used in this study to determine distances from the vibration source that the thresholds of perception (0.3 mm/s ppv) and structural damage (3 mm/s ppv) are reached.

Assuming a frequency of 20 Hz, which corresponds to the typical frequency of traffic induced ground vibrations, equations 1 and 2 suggest that heavy commercial vehicle (HCV) induced vibrations at the kerb will reduce to half of their magnitude over a distance of only 8 m perpendicular to the kerb and to a tenth of their magnitude over a distance of 80 m.

This result indicates that HCV traffic induced ground vibrations are unlikely to be problematic beyond 50 m to 100 m from source.

## 5 Estimated Construction Machinery Related Vibration Levels

The probable level of ground vibration generated by construction machinery used for the Project, has been assessed using data acquired in New Zealand for two vibrating rollers (a Sakai SW70 twin drum with an operating weight of 7,050 kg and Hamm 3410 with an operational weight of 11,000 kg) and a crawler dozer (Komatsu D65E), all operating on silty soil. These three machines can be considered representative of plant types that will be used in the construction of the Project's embankments and roads.

The measured vibrations and associated frequencies for the above 3 machines are tabulated in Table 3.

**Table 3: Representative ground vibrations generated by construction machinery**

Site	Construction Plant Make and Model	Attenuation Coefficient @ 10Hz	Operating Frequency (Hz)	Maximum Ground Vibration at 10m (ppv, mm/s)
Silt	Sakai SW70, roller	0.036	50.8	3.12
Sandy silt	Hamm 3410, roller	0.028	29.0	8.43
Sandy silt	Komatsu D65E, dozer	0.028	12.0	3.79

For simplicity, a base-line value of 10 mm/s ppv at 2m from source has been assumed for all three machines. This may be a little high for the 50 Hz Sakai roller but is appropriate for the heavy 30 Hz Hamm roller and Komatsu dozer.

The base-line value of 10 mm/s ppv at 2m was combined with the frequency dependent attenuation model (equation 1) to calculate the expected level of ground vibrations at various distances from the source. The resulting attenuation coefficients from equation 2 are 0.041 (1/m) for the 50Hz roller, 0.023 (1/m) for the 30 Hz roller and 0.010 (1/m) for the 12 Hz dozer.

Figure 2 shows the expected vibrations generated with high frequency vibrations from the rollers attenuating faster than the lower frequency vibrations of the dozer. For the vibrations to be at a level where they could cause damage to the structure of residential buildings, it is estimated that the separation distance from construction activity would have to be less than 17.5m.

In order to maintain vibration levels below the BS 5528-2:2009 perception guideline level of 0.3 mm/s ppv for residential occupants, the construction machinery would have to be operated no closer than 140m from the closest residential property. As distances less than 140m between construction activity and residences is possible on the Project, it should be noted that the BS 5528-2:2009 perception guideline level refers to a vibration level that if exceeded is likely to generate complaints. However, such complaints will be less likely if the occupants of the affected buildings are given advanced warning that the Expressway construction will generate vibrations but the level of these vibrations will be insufficient to cause structural damage. Also, it is important that the occupants are informed as to the likely timing and duration of these vibrations.

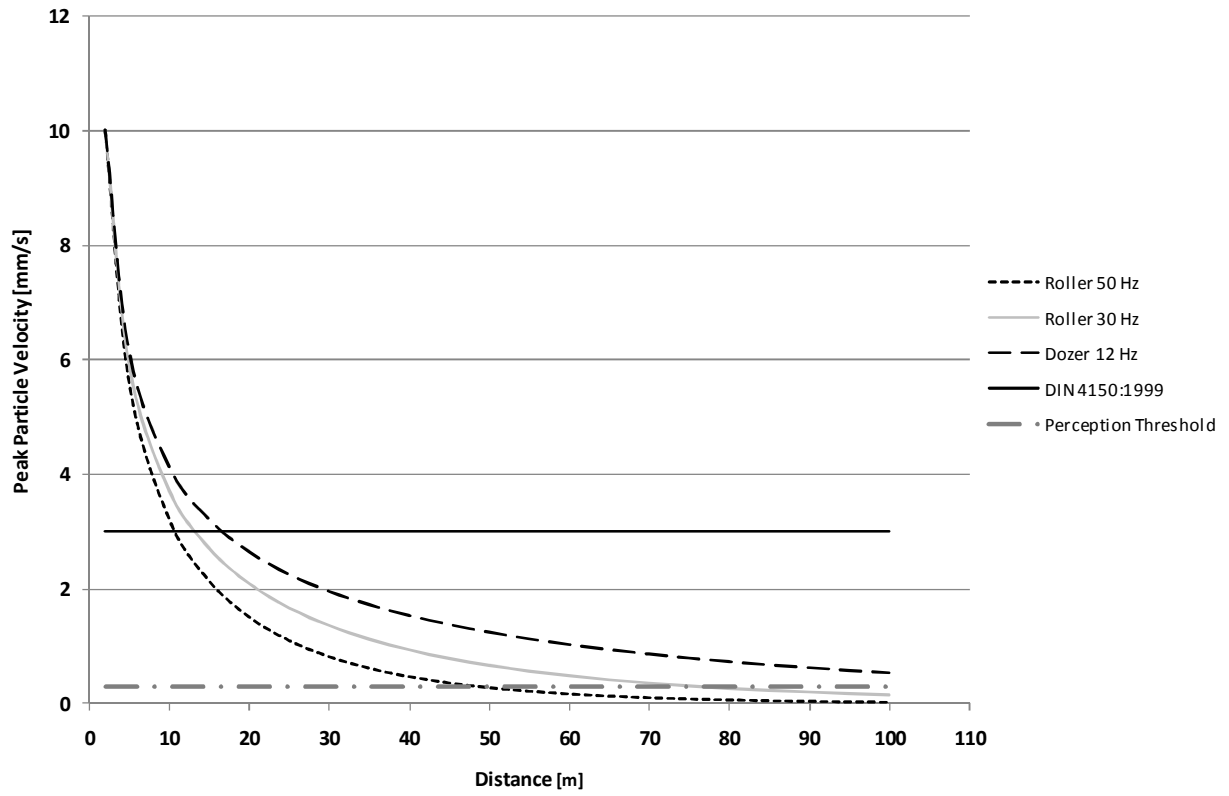


Figure 2: Predicted vibration attenuation for various construction machinery

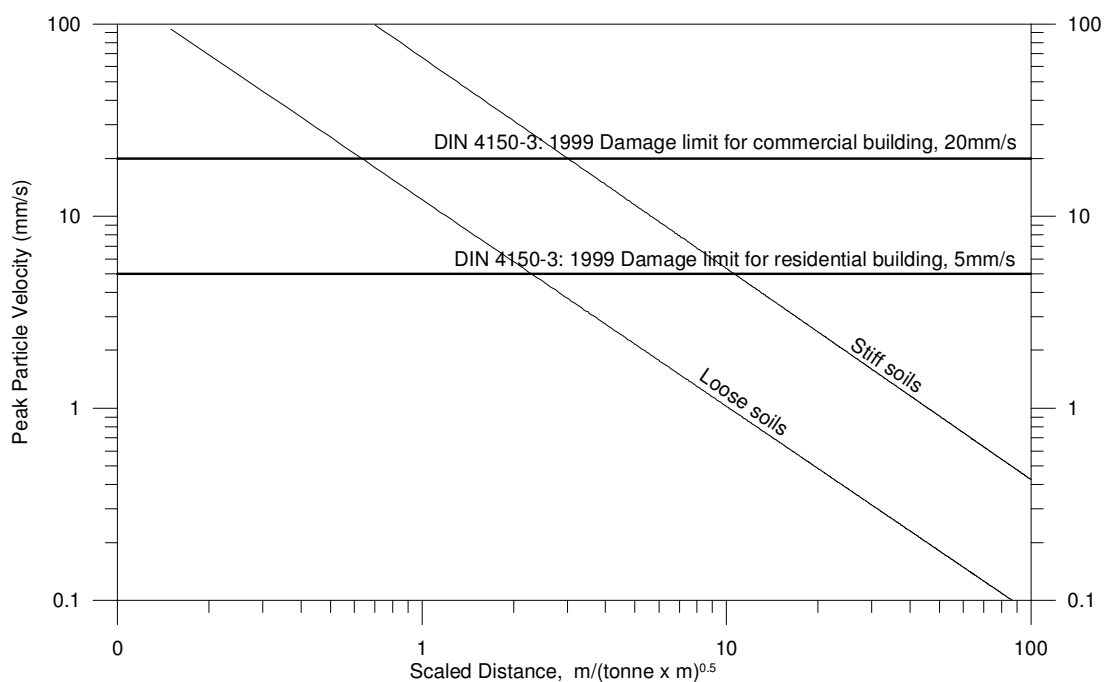
## 6 Pile Driving

Two main types of pile driving hammer are used in New Zealand, these being the impact hammer and the vibratory hammer. Impact hammers work by dropping a large weight of several tonnes onto the end of the pile and normally have a combustion process to help raise the weight before each impact. Vibratory hammers work by imparting a vertical vibration onto the pile. These hammers are particularly effective at driving piles in soils such as sand that are vibratorily mobile. Vibratory hammers also have a large stationary weight which helps to drive the pile.

### 6.1 Impact Hammers

Ground vibrations generated by dynamic compaction are presented in Dowding (2000) for a series of case studies. The maximum vibration levels from these case studies, relating to both loose and stiff soils, are graphed in Figure 3 below.

During the dynamic compaction process, the soil will progress from loose to stiff, but at any position the maximum expected vibrations will relate to the stiff soil line shown in Figure 3.



**Figure 3: Predicted vibration from dynamic compaction**

The use of scaled distance is a method of comparing energies from different energy source configurations. The scaled distance is the distance from the source divided by the square root of the drop height multiplied by the drop weight.

An expected value of peak particle velocity in mm/s can be calculated for a particular compaction setup using equation 3 below, which has been derived for stiff soils.

$$PPV = 67 \times \left( r / \sqrt{(m \times h)} \right)^{-1.1} \dots (3)$$

where: PPV is the peak particle velocity (mm/s),  
 $r$  is the radial distance from the source (m),  
 $m$  is the drop mass (tonnes), and  
 $h$  is the drop height (m).

Equation 3 above can be used to estimate vibrations from drop weight piling techniques. As an illustrative example, a drop weight of 6 tonnes and drop height of 10 m is calculated from equation 3 to generate a ground vibration of 8.6 mm/s at a distance of 50 m from the source. This would be above the DIN 4150-3:1999 damage threshold for residential buildings but within the damage threshold for commercial buildings.

Equation 3 is a particularly useful equation as it requires no knowledge of the surrounding soil type and attenuation coefficient.

Table 4 gives the maximum product of drop mass and drop height that will result in ground vibrations not exceeding the DIN 4150-3 structural damage threshold of 3 mm/s ppv for different distances from source.

**Table 4: Drop weight piling limits to prevent structural damage**

Distance from Source (m)	Drop Mass (tonnes) × Drop Height (m)
50	9
100	35
150	79
200	141

## 6.2 Vibratory Pile Driving

Vibratory pile drivers generate vibrations using eccentric rotating weights usually driven by hydraulic motors. This means that the frequency of the vibrations produced from the vibratory pile driver can be considerably higher than those produced by an impact hammer. The vibration frequency of vibratory hammers ranges from around 18-30 Hz. As mentioned earlier in section 3, vibrations with higher frequencies decay faster than vibrations with lower frequencies.

Representative ground vibration levels are available for dynamic piling operations involving sheet pile driven by an International Construction Equipment (ICE™) Vibro Hammer (216) and pile casings driven by an ICE™ 416L driver/extractor. Technical specifications of the two vibrating hammers are given in Table 5 below.

The measured vibration levels pertained to the following two vibratory piling operations:

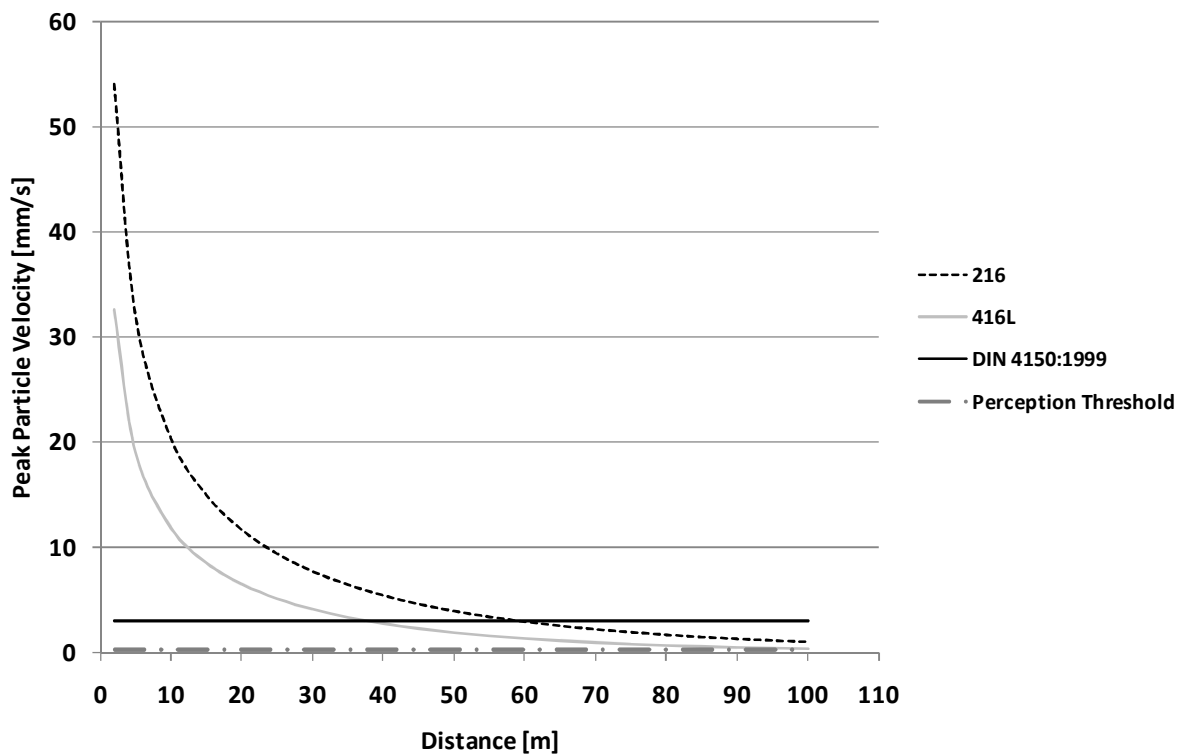
- Sheet piling using the smaller vibrating hammer (ICE™ Vibro Hammer (216)). The pile was at refusal, which generally corresponds to the worst case scenario.
- Pile casing (about 900 mm diameter) being driven and extracted using the larger vibrating hammer (ICE™ 416L).

**Table 5: Key specifications of monitored vibrating hammers**

Parameter	ICE Make/Model	
	Vibro Hammer (216)	416L
Centrifugal Force (kN)	325	645
Vibrating Weight (kg)	1.48	7
Engine Power (kW)	116	260
Eccentric Moment (kg-m)	11.5	23
Max. Amplitude (mm)	16	14
Max. Frequency (Hz)	26.7 (1600RPM)	26.7 (1600RPM)

The expected vibration levels generated by the vibratory pile drivers when operated on Waikato soils are shown in Figure 4. This indicates that the vibration levels from the two vibratory pile drivers are comparable.

With reference to Figure 4, a minimum separation distance of 57 m is required for ground vibrations to be below the 3 mm/s threshold for structural damage. This separation distance has to be increased to at least 140 m for ground vibrations to be below the 0.3 mm/s day-time threshold for occupant annoyance.



**Figure 4: Predicted vibration attenuation for vibrating hammers**

## 7 Construction Traffic

Five sites have been identified as possible sources of imported structural fill for the Project, subject to consents. They are:

- Whitehall Quarry (located on Whitehall Rd, south of Cambridge)
- Taotaoroa Quarry (located on Taotaoroa Rd, south of Cambridge)
- Airport Road Sand - Mine Quarry (located on SH21 Airport Rd, northwest of Cambridge)
- Porritt Sand - Mine (located on Hooker Rd, west of the project)
- Titoki Sands (located on Tauwhare Rd, north of Cambridge)

The most likely haulage routes are shown in Figure 5. It is anticipated that the northern access will be the main access to and from the Project site. As the Expressway embankment is constructed southwards from the Northern Interchange, heavy commercial vehicle (HCV) construction traffic will use the newly formed embankment to deliver structural fill to locations within the site. This is anticipated to limit the travel of construction traffic on local roads and through Cambridge.

The most sensitive locations from the perspective of traffic induced vibrations are associated with heavy transport movements travelling through Cambridge Township and also on the embankment as one or two residential properties on Discombe Rd are relatively close (i.e. separation distance of approximately 26 m).

In order to predict likely ground vibration levels induced by construction traffic, the models detailed in the US Federal Highway Administration Report FHWA-RD-78-166 "Engineering Guidelines for the Analysis of Traffic-Induced Vibration" (Rudder, 1978) have been applied. These models allow ground vibration levels to be predicted as a function of road surface roughness, vehicle speed, gross vehicle weight and distance from kerb edge. Opus' experience with the FHWA models suggests that they produce conservative estimates of maximum probable ground vibration whenever the road surface has random roughness

The NZTA's RAMM database was interrogated to find the highest 20 m averaged values of lane roughness over 50 km/h and 100 km/h sections of SH1B through Cambridge (i.e. SH1B-RS30/11.954 – 15.854) for the 2009/2010 HSD survey. These were 154 NAASRA counts/m and 177 NAASRA counts/km respectively. For the Expressway embankment, a lane roughness of 250 NAASRA counts/km was assumed, corresponding to an unsealed road in good condition.

The other modelling assumptions were as follows:

- A maximum permitted weight for the truck and trailer unit of 44 tonnes.
- Truck and trailer units travelling at the posted speed limit.
- A conservative attenuation factor of 0.008, corresponding to an exciting frequency of 10 Hz which is at the lower end of unsprung mass (wheel bounce) frequencies for both "walking beam" and air suspensions of HCV's.

The results of the modelling are presented graphically in Figure 6, in which vibration levels at different distances from the kerb for the four different speed and roughness scenarios of interest are plotted.

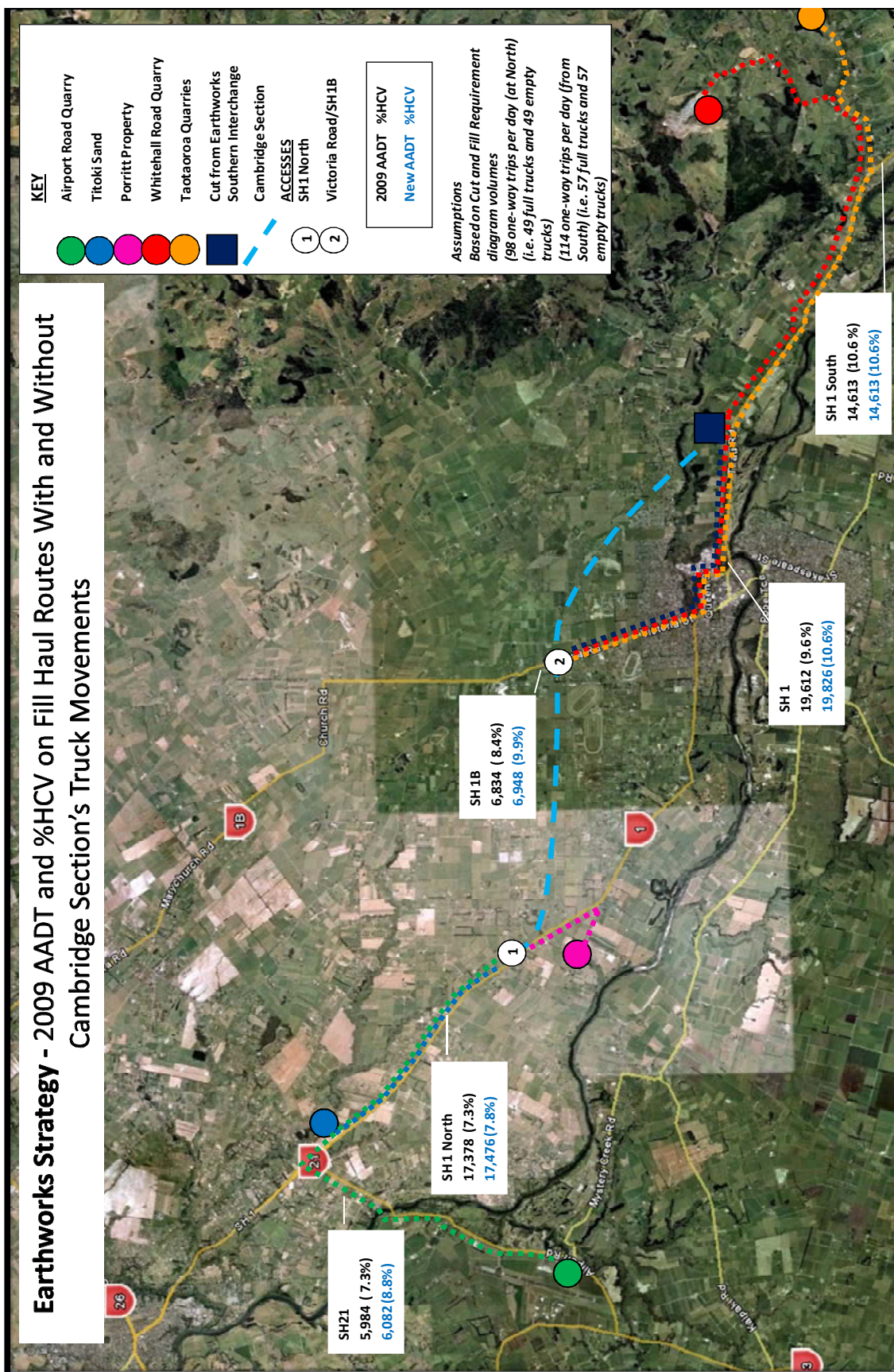
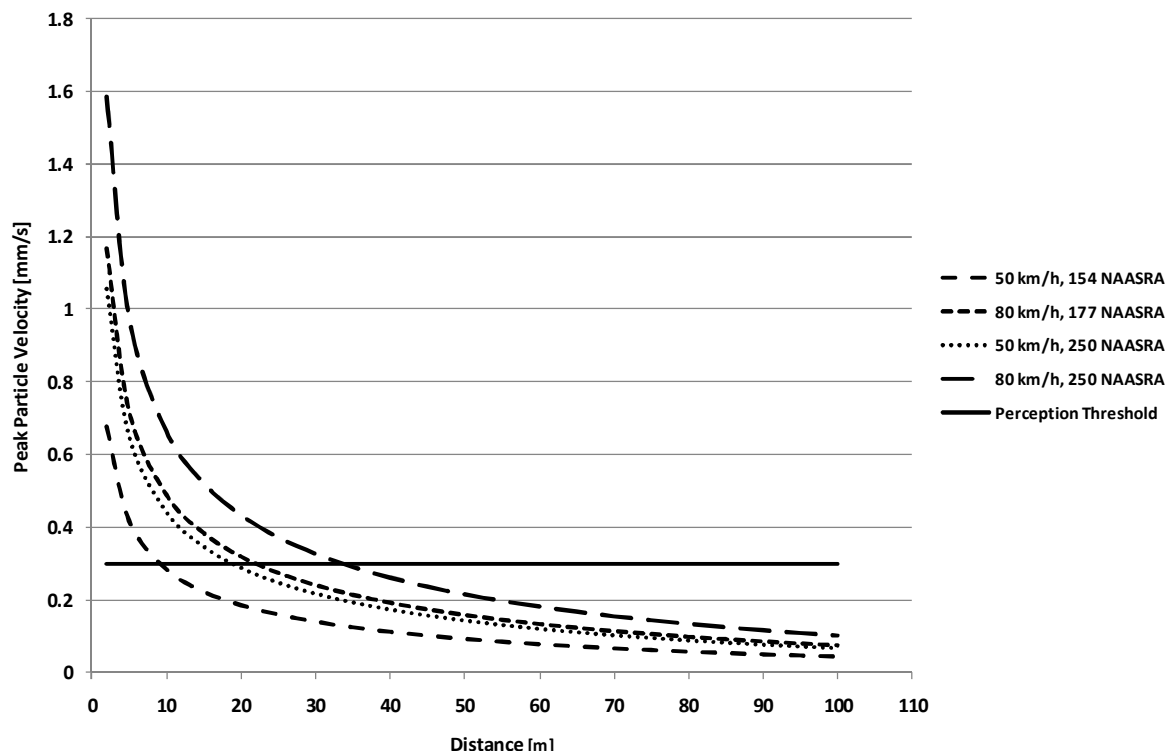


Figure 5: Fill haul routes



**Figure 6: Predicted attenuation of HCV traffic induced ground vibrations**

With reference to Figures 6, it is clear that there is very little possibility of a significant detrimental impact on any structure as a result of ground vibration arising from construction traffic associated with the Project. Therefore, the discussion below focuses on human response to traffic induced ground vibration from the Project.

Construction traffic travelling through Cambridge Township will not adversely impact on present conditions as speeds travelled and loads carried will be the same as existing HCV traffic. Figure 6 indicates that in the Cambridge Township, the perception threshold guideline of 0.3 mm/s ppv is unlikely to be exceeded for speeds of 50 km/h and below if properties are 9 m or further away from the kerb. Over the high speed section, where HCV traffic can travel at 80 km/h (i.e. SH1B RS30/12.8-14.7), this critical separation distance increases to 22 m.

The critical issue with regard to traffic induced vibrations appears to be associated with the use of the newly formed embankment to deliver structural fill to locations within the site. Some residences are located as close as 26 m to the embankment, these being 245A and 251 Discombe Rd. Figure 6 indicates that the perception threshold guideline of 0.3 mm/s ppv will be exceeded if the distance between the traffic and a residence is less than 34 m for a travel speed of 80 km/h, assuming the road surface is unsealed. However, if the travel speed is reduced to 50 km/h, the critical separation distance reduces to 19 m.

Consideration should therefore be given to the speed fill haulage operators expect to be travelling over the Expressway embankment to ensure the road surface is constructed to an appropriate roughness level so as not to cause vibration levels that are annoying to nearby residents. Table 6 provides guidance in this regard.

**Table 6: Maximum road roughness to limit HCV traffic induced vibrations to 0.3 mm/s ppv at 26 m from the edge of the road**

Haulage Speed (km/h)	20m averaged lane roughness (NAASRA counts/km)
40	700
50	350
60	260
70	220
80	195

These results highlight the sensitivity of ground vibrations to the longitudinal roughness characteristics of the road surface and vehicle speed.

The predicted vibrations discussed above assume a homogeneous road surface. Shock loading from bumps or potholes or regularly spaced corrugations that induce resonance in HCV suspension systems have the potential to generate ground vibrations that are considerably above the level normally associated with HCV traffic.

Impact or resonance induced ground vibration problems could occur at joints and in areas where deformation of existing roads occurs due to heavier and more frequent traffic. Therefore, care should be taken to ensure the selected haulage routes are relatively free of localised corrugations. They also should have sufficient strength to carry the HCV traffic expected so that the formation of surface defects that lead to rapid roughness progression (i.e. rutting, potholes, surface cracking etc.) can be minimised.

## 8 Operational Traffic

The probable maximum ground vibrations at the verge of a road arising from traffic is calculated using an approach developed for the US Federal Highway Administration (Rudder, 1978), which provides a value for the peak particle acceleration two metres from the edge of the road.

The criteria used for evaluating the effect of vibrations on humans and buildings are formulated around peak particle velocities. Therefore, the following transformation was employed for this assessment:

$$\text{peak particle velocity (mm/s)} = \frac{1000 \times \text{peak particle acceleration (mm/s}^2\text{)}}{(2 \times \pi \times f)} \dots (4)$$

where  $f$  = axle bounce frequency (Hz)

The typical axle bounce frequency for heavy commercial vehicles ranges between 8-15 Hz for “walking beam” suspensions and 10-15 Hz for air suspensions. For this analysis, an axle bounce frequency of 10 Hz was assumed as this corresponds to the lowest frequency that covers both suspension types. With reference to Equation 4 above, a low bounce frequency will give “worst case” (i.e. conservative) estimates of peak velocities.

Vehicle weight and speed and a factor related to the roughness of the road surface are required as inputs to the predictive model. For this investigation, the maximum permitted weight of 53 tonnes for high productivity vehicles (HPMV) and a vehicle speed of 90 km/h, corresponding to the open road speed limit for all heavy vehicles, have been assumed.

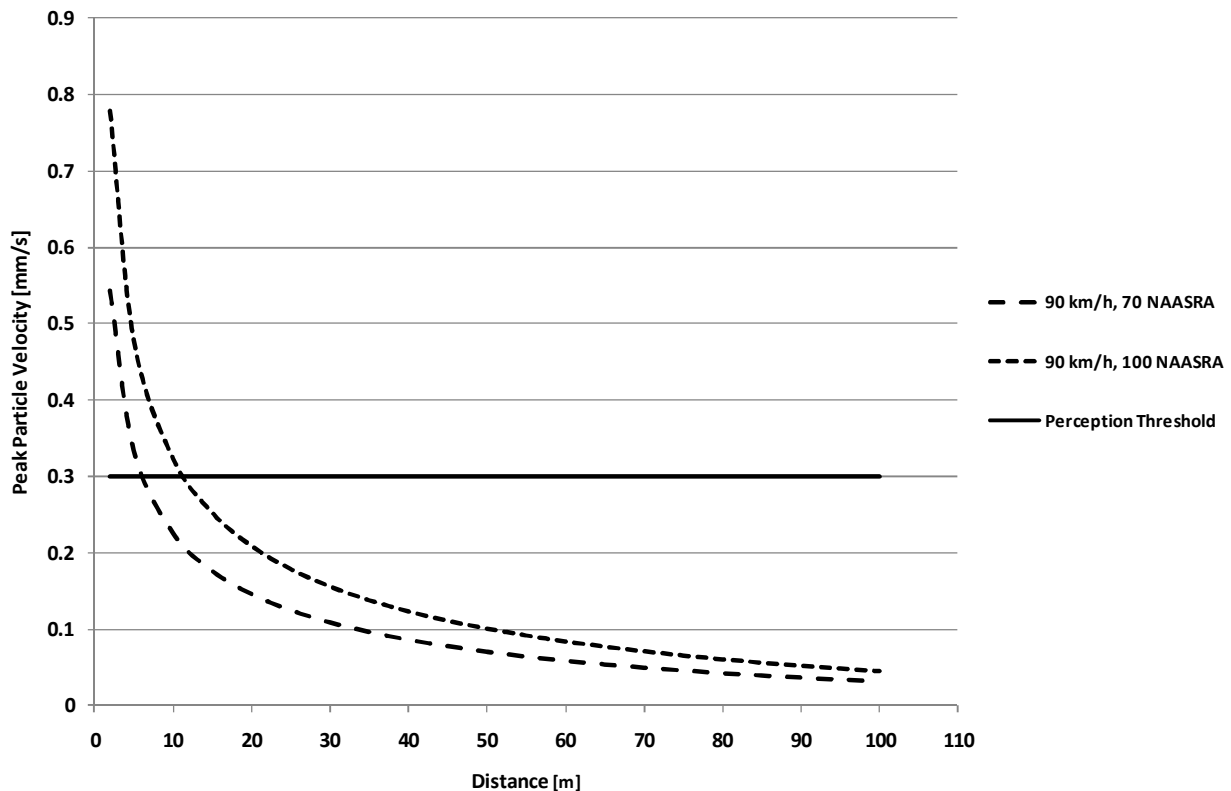
The NZTA’s roughness requirements for new road works, as outlined in Technical Memorandum TNZ TM 7003 v1, is that no 100 m moving average of lane roughness over the extent of the works shall exceed a maximum of 70 NAASRA counts/km, with the target value being 60 NAASRA counts/km. For structural asphaltic concrete or other bituminous surfacings, the maximum and target 100 m moving average lane roughness requirements are reduced to 60 and 50 NAASRA counts/km, respectively. The NZTA also has as a performance target for road roughness that not more than 1% of the roughness counts by length and vehicle kilometres travelled should exceed a guideline value of 100 NAASRA counts/km for motorways and expressways.

Therefore, the two roughness scenarios modelled in this assessment were:

1. A lane roughness value of 70 NAASRA counts/km, which corresponds to the expected roughness when the Expressway is new. Coincidentally, this level of roughness is close to the average roughness level of New Zealand’s State highway network (NZTA, 2009).
2. A lane roughness value of 100 NAASRA counts/km corresponding to the worst case of an expressway surface near the end of its useful life.

It should be noted that this investigation does not apply to roads with potholes or badly reinstated trenches, where vehicle impact can generate significant ground vibration or for roads with uneven shape that induces resonance in the suspension of heavy vehicles.

The attenuation of the predicted traffic induced vibrations was estimated using equations 1 and 2 given in Section 3 of this report with  $R_1$  set to 2 m and  $\alpha$  set to  $0.009 \text{ (m}^{-1}\text{)}$ . Figure 7 shows the resulting ground-borne vibration levels relative to distance from the kerb edge for the two scenarios considered with the relevant guideline limits superimposed.



**Figure 7: Predicted range of ground vibration levels induced by operational traffic**

The residences in closest proximity to the Project, being 245A and 251 Discombe Rd, will be a distance of about 26 m from the road edge, while the majority of the other residences bordering the Project will have a typical separation distance of about 50 m.

With reference to Figure 7, it is clear that so long as the maximum lane roughness and maximum speed of heavy commercial traffic are maintained to 100 NAASRA counts/km and 90 km/h respectively, occupants of existing buildings adjoining the Expressway are unlikely to be able to perceive the ground vibrations induced by traffic.

## 9 Discussion of Results

### 9.1 Vibrations from Construction Activities

The closest residences to the Project are 245A Discombe Rd, 251 Discombe Rd and 276 Tirau Rd. The separation distance for the Discombe Rd residences is estimated to be 26 m and for the Tirau Rd residence 30 m. By comparison, the distance of properties from the expressway in the area from Watkins Rd to the Karapiro Gully highlighted in the Introduction as being potentially vibration sensitive is approximately 40 m.

From the analysis undertaken, ground vibrations exceeding the threshold value for damage to residential structures given in the German Standard DIN 4150-3 of 3 mm/s ppv can be generated within a radial distance of 25 m to 40 m for impact and vibratory hammer piling, 10m to 15m for vibratory rollers and about 20 m for slow revving dozers and motorscrapers.

Therefore, the only construction activity capable of causing structural damage on the Project is pile driving. For this reason, particular care should be taken in selecting impact and vibratory hammer configurations for pile driving works to ensure ground vibration levels at the nearest residential buildings to the piling are below 3 mm/s ppv.

The threshold value for perception given in the British Standard BS 5528-2 of 0.3mm/s ppv can be generated within a radial distance of 105 m to 140 m for impact and vibratory hammer piling, 48 m to 75 m for vibratory rollers, about 140 m for slow revving earthwork machinery such as dozers and motorscrapers and 5 m to 15 m for construction traffic operating on sealed State highways.

Vibration levels above 0.3 mm/s ppv can disturb, startle, cause annoyance, interfere with work activities and promote anxiety in residential accommodation for fear that some structural mishap may occur. Therefore, prior warnings of construction activities causing large ground vibrations should be distributed to all residences within 140 m of construction zones where either piling or earthworks is taking place.

In the case of construction traffic travelling on State highways and local sealed roads, vibrations exceeding the perception threshold can be confined to within 5 m of the source provided the road surface is free of localised corrugations and potholes (i.e. expected 20 m lane roughness of about 70 NAASRA counts/km). Should this not be the case, local smoothing works should take place before construction traffic commences as road sections with high localised roughness induce high dynamic tyre loads that in turn generate stress waves which propagate in the soil, reaching foundations of adjacent buildings and causing them to vibrate.

### 9.2 Vibrations from Operational Traffic

The study indicates that buildings would need to be located 20 m or closer to the Expressway before vibrations generated by traffic could be perceived by building occupants. As the closest existing building is estimated to be 26 m away, traffic induced vibrations are unlikely to be problematic provided existing NZTA's maintenance practices in regard to road roughness management are adhered to.

The only potential issue regarding operational traffic relates to the possibility of impact induced ground vibrations caused by joints in the road surface. These joints occur at bridge abutments and

whenever there is a change in surface type. Therefore, care should be taken to ensure smooth transitions at such locations.

## 10 Concluding Remarks

The principal findings arising from the desk study of ground vibrations generated by construction and use of the Cambridge Section of the Waikato Expressway are summarized below.

1. Vibrations from general construction activities are unlikely to produce vibrations that will exceed the German Standard DIN 4150-3:1999 limits for building damage, apart from impact and vibratory hammer piling used in the construction of the bridge structures.
2. Vibrations from pile driving are likely to be the largest vibrations caused by the construction. These activities should be assessed on a case by case basis, firstly using predictive models to confirm that the planned pile driving operations are appropriate for the available separation distances between where the construction activity is taking place and nearby buildings and secondly field measurements when this type of construction activity is taking place to confirm the predicted vibration levels. This will minimise the likelihood of any structural damage being inflicted on existing buildings.
3. Only buildings that have a separation distance less than 140m from the edge of construction activity are predicted to experience vibrations from general construction operations that are in excess of the perception guideline of 0.3 mm/s peak particle velocity given in the British Standard BS 5228-2:2009.
4. The critical issue with regard to traffic induced vibrations appears to be associated with the use of the newly formed Expressway embankment to deliver structural fill to locations within the site. This is because some residences are located as close as 26 m to the embankment. Therefore, consideration must be given to the speed fill haulage operators expect to be travelling over the embankment to ensure the road surface is constructed to an appropriate roughness level so as not to cause vibration levels that are annoying to nearby residents.
5. Road sections with high localised roughness induce high dynamic tyre loads that in turn generate stress waves which propagate in the soil, reaching foundations of adjacent buildings and causing them to vibrate. Therefore, it will be prudent to target smoothing works before construction traffic commences wherever construction traffic travels on State highways and local sealed roads, Ideally, the maximum 20 m roughness should be 110 NAASRA counts/km for 50 km/h roads and 76 NAASRA counts/km for 80 km/h roads to achieve a vibration level of 0.3 mm/s ppv 5 m from the source.
6. Vibrations induced by traffic once the Expressway is operational are unlikely to be perceived by occupants of existing adjoining buildings so long as the maximum roughness of the road surface is maintained to 100 NAASRA counts/km or less, which is current NZTA practice for motorways and expressways, and the maximum speed of high productivity motor vehicles is limited to 90 km/h.

The above findings lead to the following three actions being taken to ensure ground vibrations generated by the construction and operation of the 10.4 km long Cambridge Section of the Waikato Expressway will not be problematic.

1. A vibration management plan will be prepared by the contractor, as part of the Construction Management Plan, potentially in conjunction with a construction noise management plan, in order to limit the duration of nuisance-level vibrations during the construction period. It is likely that this vibration management plan will specify the use of smaller vibrating rollers operating at very high frequency levels in areas where the vibrations are expected to be problematic. Prior warnings of construction activities causing large ground vibrations will also be given to affected residents, which will include the likely timing and duration of the vibrations and any information on the likelihood of structural damage to neighbouring buildings. The vibration management plan will also specify pre-construction inspections of all buildings within 50 m from the edge of any earthworks activity to allow confirmation of any structural damage claims. The 50 m distance has been selected as it is predicted that at this distance vibrations will be about 1 mm/s ppv, corresponding to the British Standard BS5528-2009 threshold for complaint in residential environments.
2. To minimise the likelihood of impact induced ground vibrations from passing traffic, care will be taken at joints along the Expressway, formed at bridge abutments and between different road surfacing types, to ensure the transitions are as smooth as possible.
3. The decay of vibrations with distance has been predicated on an attenuation coefficient ( $\alpha$ ) that is dependent on the frequency ( $f$ ) of the ground vibrations as follows:  $\alpha = \rho\pi f$ . The parameter  $\rho$  is a frequency independent material property of the soil, which has been estimated from limited measurements to be 0.0003 (s/m) for Waikato soils. To confirm the suitability of this value of  $\rho$  for assessing vibrations generated by construction and operation of the Expressway, site measurements of traffic vibrations will be made along the proposed SH1B fill haul route. These measurements will also be used to provide a record of existing traffic vibration levels and to confirm the model predictions of the effect of mass, speed and road roughness on traffic induced ground vibration levels.

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