FACTORS AFFECTING TRAFFIC-GENERATED VIBRATIONS ON STRUCTURES AND THE MASONRY MINARET OF LITTLE HAGIA SOPHIA

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Abstract
Increasingly buildings and their occupants are negatively impacted by traffic–induced vibrations. The continuous application of vibrations is particularly detrimental for historic masonry buildings and for very modern structures constructed of strong and light materials. Population and land development trends indicate greater proximity of traffic flow near buildings in coming years. This paper outlines the factors influencing the frequency content and the magnitude of vibrations on nearby structures in an attempt to enable local communities and their designers to be more proactive in vibration mitigation. Using these described factors, the paper assesses the effects of traffic-induced vibrations on a portion of a monumental masonry building: the minaret of Little Hagia Sophia Mosque (former Byzantine Church of the Saints Sergius and Bacchus) based on adjacent railway field measurements.

Keywords: Dynamic response, human annoyance, Little Hagia Sophia Mosque, masonry structures, minarets, traffic-induced vibrations

1. Introduction
Ground vibrations due to earthquake and blasting have been studied more extensively than other vibration sources such as road and rail since the effects of the former are more dramatic and sudden. However, transport-induced vibrations may damage adjacent buildings, cause human discomfort, and disrupt sensitive equipment and manufacturing, because of their long-term and repetitive nature. Global urbanization has brought unprecedented population densities adjacent to transportation routes, with increasing quantities of road and rail traffic (Figure 1). Although considerable numerical simulations and experimental studies have been conducted to predict the negative effects of these vibrations, the factors affecting the impact of traffic-induced vibrations and their consequences have not been fully categorized. Therefore, this paper aims to address and establish, in a systematic way, the factors influencing the range of frequencies and vibration amplitudes that are most detrimental to existing structures, by evaluating the response of the minaret of Little Hagia Sophia Mosque, because this tall and slender masonry structure is extremely close to a heavily trafficked train line and has not been investigated regarding train-induced vibrations. This will help conserve cultural heritage and assist in devising mitigation for existing disturbances.
2. Factors affecting the impact of transport-induced vibrations

A key component to assessing transport-induced vibrations is understanding under what conditions vibrations reach amplitudes exceeding those thought to disturb building occupants and damage buildings. Peak particle velocity (PPV), namely the maximum velocity of the wave transmission is often used as the limiting factor (Table 1).

Table - 1 Sampling of Published Vibration Threshold Values for Buildings and Occupants

<table>
<thead>
<tr>
<th>Peak Particle Velocity (mm/sec)</th>
<th>Effect on Human or Buildings</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>Perceptible for human</td>
<td>(Wiss 1981)</td>
</tr>
<tr>
<td>0.8</td>
<td>Distinctly perceptible for human</td>
<td>(Wiss 1981)</td>
</tr>
<tr>
<td>2.5</td>
<td>Strongly perceptible for human</td>
<td>(Wiss 1981)</td>
</tr>
<tr>
<td>5</td>
<td>Risk of architectural damage</td>
<td>(Whiffin and Leonard 1971)</td>
</tr>
<tr>
<td>10</td>
<td>Vibrations can cause minor structural damage on buildings</td>
<td>(Whiffin and Leonard 1971)</td>
</tr>
</tbody>
</table>

2.1. Factor 1: Vehicle features

Vehicle mass has a significant effect on traffic-induced vibration levels (Papagiannakis and Ravendran 1998). A larger mass leads to larger inertial forces on pavement, thereby producing larger ground-borne vibrations. These are primarily due to heavy vehicles. Vehicle dimensions are also important. For instance, the delay between the passages of each axle influences the frequency of loading and, thus, the frequency content of the ground-borne excitation. Additionally, in-situ measurements have shown that higher amplitude vibrations occur for higher vehicle velocities. Equally, the vibrational characteristics of the vehicle are significant. Jerry et al. (2006) provide the following examples: (1) a steel-leaf, spring suspension system of a truck produces more dynamic forces and vibrations than an air suspension systems; (2) stiff, over-inflated tyres bounce more readily over surface irregularities, thereby resulting in higher dynamic forces; and (3) the braking system and the rate of acceleration and deceleration also contribute to the generation of vibrations.

2.2. Factor 2: Vehicle–road–track interaction characteristics

The road and track surface conditions and their mechanical properties play a crucial role in the ultimate PPV levels. Specifically, flexible pavements absorb more energy than stiff pavements. Pavement roughness caused by cracks, potholes, bumps, and even uneven manhole covers (and similar often uncontrolled features) drive a dynamic
response in a passing vehicle and hence contribute significantly to ground vibrations (Figure 2). These surface irregularities cause randomly occurring dynamic forces up to 15% higher than the corresponding static forces (DIVINE 1997). However, periodic and discrete pavement irregularities effects can be even more severe, causing more than an 80% increase in dynamic forces (Jerry et al. 2006). When potholes or bumps are more than 25 mm in depth/height or 150 mm in length these can cause ground peak particle velocities (PPVs) of around 5 mm/second, which is noteworthy as a PPV of 5 mm/sec has been proposed as a limit to prevent architectural damage in houses with plastered walls and ceilings (Whiffin and Leonard 1971). Similarly, since both train rail and wheels can have defects such as corrugation, stiffness variation, joints, and wheel flats, additional dynamic loads can be produced up to 50% of the wheel load (Profillidis 2000).

**Figure 2 - Cracks on the Road Surface – Donnybrook, Dublin**

### 2.3. Factor 3: Propagation of waves through soil
While traffic-induced stress waves propagate through soil, the propagation wave characteristics depend significantly on the distance from the source, the soil properties, soil profile and topography, and the adjacent structure characteristics. Vibration amplitude diminishes with distance due to expanding surface and material damping. Material damping is related to soil type, moisture content, and soil temperature (Dowding 1996). For example, dry sand and gravel soils have the highest capability to absorb vibration, while soft clays have the lowest (Watts 1992). There are even cases where the layered soils have caused wave amplification. As an example, Hunaidi and Tremblay (1997) reported that traffic vibrations appear worst in areas underlain by a soft silty clay layer between 7 m and 15 m deep. Furthermore, seasonal variations of the ground water table changes response properties as saturated soil result in lower compressibility and higher density (Schevenels et al. 2004).

### 2.4. Factor 4: Soil-structure interaction characteristics
While vibrations are transmitted from the ground to a building’s foundation, both the foundation type and the soil-structure stiffness interaction play important roles. François et al. (2007) concluded that no building wall deformation occurs, if a building is resting on a soft soil, and the global structural response is dominated by rigid body kinematics. If the soil is stiff with respect to a building, however, the building walls deform in a quasi-static way, following the ground motion. Additionally, the presence of a (stiff) foundation prevents the transfer of energy into the structural system. Therefore, wall cracking caused by excessive deformations is more likely to occur when a soft structure rests on a stiff soil.

### 2.5. Factor 5: Structure features
If traffic-induced vibration frequencies are similar to those of a building’s natural frequencies, resonance occurs (Hunaidi et al. 2000). In such cases, vibration reduction can be achieved by judicious stiffening of the structure for a particular vibration mode. For resonant excitation, the most critical case is excitation of the first natural frequency of the building (Ju 2009) – then, unfortunately, structural interventions to alleviate vibration response can be hampered due to the global response of the structure in its first mode of vibration. However it is usually the frequencies of the higher modes of vibration of structures that tend to coincide with the principal frequencies of traffic-induced ground motions. In particular, as buildings become taller, higher modes for individual floor levels are more likely to be excited by adjacent vibrations. Furthermore, when the modal mass participating ratios are sufficiently large at higher modes, significant amplification of vibration response is possible (Erkal et al. 2010a).

3. Case Study: Minaret of Little Hagia Sophia
To understand how these factors converge, a case study is presented. Minaret response to vibrations is a well-established concern, especially in seismic zones (Gentile and Saisi 2007). There have been a number of studies including El-Attar et. al’s (2005) work on the potential benefits of base-isolation for reducing the seismic vulnerability of Mamluk-style minarets and Dogangun et. al’s (2008) analysis on three masonry minarets of varying heights using two earthquake ground motions. They suggested fibre reinforced polymer composite wraps or reinforcement for retrofitting based on numerical investigation of dynamic behaviour and response. However, adjacent transport-induced vibration impacts on minaret structures remains unexplored. Here, the minaret of Little Hagia Sophia Mosque is assessed in relation to train traffic due to its extreme proximity to the railway (Erkal et al. 2010b, Yuzugullu and Durukal 1994).

A vibration measurement program was performed on the masonry structure Little Hagia Sophia Mosque located in the district of Eminonu in Istanbul, adjacent to the Sirkeci-Halkali railway line. The mosque, formerly the Church of the Saints Sergius and Bacchus, was built in the period 527-536, AD, as a model for the Hagia Sophia. During the Ottoman Empire (1506-1513) it was converted into a mosque. In 1762 a minaret was first built but demolished in 1936. The current minaret was built in 1955. The height and slenderness of a minaret makes it particularly vulnerable to ground movements (Figure 3). This minaret of cut stone is only 10.5 m from the heavy railway line (north-south direction) as shown in Figure 4 in plan view with the mosque and minaret, and the instrumentation.

Figure 3 – Minaret as a Single Structure next to the Mosque
The instruments were placed equi-distantly along the minaret’s height up to the minaret balcony (Figure 4-b). Seismographs are labelled as A-D, and the preceding number indicates the test no [e.g. 10A means instrument A in Test 10]; the other tests were conducted elsewhere on the property. Three perpendicular components of ground motions (east-west, north-south, and vertical) from four trains were measured. Four ultra-lightweight, digital output seismometers (CMG-6TD) were used. The seismometers are ideally suited for sites where there is medium level of background vibrations. Owing to the possible high stiffness of the masonry buildings and high frequency nature of vibrations, sampling rate was assigned at 500 samples per second to allow a broad range analysis; 2.5 times greater than the value chosen in the study of ambient vibration testing of a masonry bell-tower (Gentile and Saisi 2007).

Regarding loading, 118 suburban and 6 intercity passenger trains in addition to 2 freight trains pass by the minaret (1 approximately every 10 minutes) daily (TCDD 2010). These transport 65,000-75,000 people using trains of 6 cars – 2 of which are locomotives, which pull from either end depending upon journey direction.

4. Discussion of the factors considering the minaret
Since most codes and studies rely on a PPV to evaluate the severity of traffic-induced vibrations, PPVs, were measured at four points of the minaret (Figure 5). Although the PPVs were not sufficiently large to generate severe structural damage, in some cases, the vibration levels exceeded the lowest damage PPV threshold found in literature (1mm/sec) (Domenichini et al. 1998), although this is exceptionally low compared to most of what is reported in the literature. Most of the PPV values were larger than 0.3mm/sec as being perceptible to human body (ISO 1989), and some of them larger than 0.8mm/sec as distinctly perceptible (Wiss 1981). Vibration levels were as high as 1.25mm/sec at the balcony level in the north-south direction (Figure 5).
Regarding vehicle and rail features, the train weighs 3,200kN (carriage axle weight: 140kN and 4-axle locomotives weight: 160kN). Axle weight for freight train locomotives is 200 kN, which could be critical, as Celebi (2006) also mentions that the increase in passenger transport at high speeds, with heavy-loaded trains or giant lorries will cause strong ground and structural vibrations in intensively populated urban areas. This type of vibration in the frequency range of 4–50 Hz may cause some structures to resonate with their vibrating modes. In the study reported herein, train velocities spanned 70-90km/h, similarly to that reported by Xia et al. (2005), who noted that when train speed increased from 60km/h to 80km/h, maximum ground level vibration increased by 23%.

In relation to soil and soil-structure interaction features, the site’s clay and marl of the early pliocene period is cohesive and composed of fine particles. The soil is very heterogeneous and heavily layered. A pit excavation beside the minaret showed the top 90 cm to be new fill with plant residue, silt, brick rubble, and bone. Beneath that was old fill with 20-30% of gravelled greyish limestone covered with clay-marl lithology and many coal and glass pieces to a depth of 2 m [Arun and Akoz 2003].

In terms of structural features, although the largest PPV values mostly occur at the higher levels, the response is not uniformly greater with height (Figure 5). This is attributable to the fact that the principal excitation frequencies associated with traffic activity are likely to be higher than the lowest natural frequencies associated with the minaret. In other words, contribution of higher modes to the overall response of the minaret is significant. A similar observation was made by Dogangun et al. (2008), in the analysis of 3 masonry minarets (20, 25, and 30m in height). Based on modal analysis, they reported that the contribution of higher mode effects to total dynamic response was significant. Additionally, modal and time history analyses of the minarets have shown that the structural periods and the overall structural response are influenced by the minaret height and spectral characteristics of the input motion.

**Figure 5 PPV Vibration Levels along the Height of the Minaret**
Conclusions and future work
Five factors influencing the transport-induced vibration characteristics on nearby structures have been explained and discussed in a systematic way in relation to a vibration-susceptible masonry tower structure - the minaret of Little Hagia Sophia Mosque in an attempt to enable communities to be more proactive in vibration mitigation. Current practice in building vibration assessment, due to traffic loading, is guided by a single threshold value. Therefore, there is an urgent need for further research to establish a parametric set of quantified input variables and to directly relate those to the five areas outlined in this paper. Such knowledge would allow a change in codes to mitigate the impact of traffic-induced vibrations in the design stage and to effective remedy methods for existing structures. Future work will include the finite element modelling and evaluation of vulnerable structures to traffic-induced vibrations for further comparison with field measurements.

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References


TCDD, Turkiye Cumhuriyeti Devlet Demiryollari (2010), Railway Organization of Republic of Turkey, http://www.tcdd.gov.tr/


