RAIL SYSTEM NOISE AND VIBRATION CONTROL

George Paul Wilson

Wilson, Ihrig & Associates, Inc., 5776 Broadway, Oakland, California 94618, USA

Abstract

Control of noise and vibration emitted by steel wheel and rail transportation systems has a long history of designs and techniques, some of which were dismal failures and some which worked very well. Many of the early efforts had a valid technical base for the design, however, there were also many based on intuition or ideas with great expectations, but which had no real technical basis. In the last four decades the technology and materials used for rail noise and vibration control, particularly for the control of groundborne vibration from rail systems, has developed and benefited from thoughtful technical analyses and application of simple engineering principles. These also were not always successful in all respects but provided for a continuing development of the technology with ever-improving success and performance. Included in this presentation are a review of the development of rail noise and vibration control systems, including the lightweight, undamped concrete floating slab track for reduction of groundborne noise and vibration, and of the development of structurally integrated sound barriers with absorption materials for control of airborne sound. The presentation includes anecdotes and discussion of some of the unexpected results from new design installations, an outline of design progress and application extensions, and review of the concepts and designs which are successful and currently in use by rail systems located in many different parts of the world.

Introduction

There has been impressive progress over the last 40 years in the development of rail system noise and vibration control technology and designs. Design criteria for rail system noise and vibration were once either not considered or treated as a secondary item but the importance as a major design parameter is now recognized by new system designers. Sometimes there is still resistance to incorporation of non-revenue producing features in the rail system design, but as each new generation of project managers and designers become educated, there is acceptance of the need for incorporation of noise and vibration control in the overall system design.

In the mid-60's when I began work with assessment and control of noise and vibration from rail systems there were three new rail transit systems in design development: the San Francisco Bay Area Rapid Transit District, BART; the National Capital Transportation Agency, now the Washington, D.C. Metro; WMATA, and the Baltimore Region Rapid Transit District, BRRT. These were the first major new rail transit facilities that had been considered in the United States since the 1930's. In Toronto, Canada the TTC Yonge Subway was opened in 1954 and was the first subway to be built in North America since the beginning of WWII. This was the first North American system to use resilient rail fixation on concrete. Extensions were opened in the period from 1963-1968 and with 34 kilometers total it became the catalyst for resurgence of rail or fixed-guideway transit on the North American continent.

Because of the negative image created in the U.S. by the very noisy steel elevated structures in Chicago and New York, new transit system planners did have concerns about noise and vibration. As a result, studies and surveys were commissioned to develop information which could be used to set new facility design criteria. One of these surveys completed for the Washington, D.C. Metro, by the Office of Research and Experiment, ORE, of the International Railway Union, UIC, asked ORE members to rank order operational problems. The result was almost universal ranking of (1) vandalism and (2) noise and vibration as the two top priority problems.

Partly as a result of the survey, but also because of the general concern regarding patron exposure to noise and vibration and the effects on adjacent communities, a large number of measurement programs and research studies were completed in the 1960's and '70's. One survey by ORE published in 1981 listed 192 separate reports produced or published during the period from about 1965 to 1979 on various aspects of rail system noise and vibration, including standards or regulations and exposure or annoyance assessment.

The studies and experiments with rail system noise and vibration included a number of trial installations of resilient rail fixation designs and floating slab track for reduction of the ground and structure-borne noise. Examples include the Paris Metro in coordination with the Regional Express Line, RER, and the French National Railway, SNCF, installing a number of test tracks with of various rail fastener designs and floating track slab. German railways also were experimenting with resilient rail fixation on concrete. In Vienna, floating track slabs supported on continuous glass fiber panels were installed in an effort to reduce groundborne noise from streetcar lines. In Toronto several trial installations of floating slab track using polystyrene foam boards as the isolation media were installed. The Paris Metro installations provided valuable information on performance of various resilient track fixation systems. The continuously supported track slabs in Vienna and Toronto were not successful.

Much of the concern relative to noise and vibration in new rail systems was with respect to the in-vehicle noise and ride quality. These were perceived as affecting the attractiveness of public transit to the patrons and, therefore, directly related to revenue. This made in-vehicle noise and ride quality very important design parameters. Thus, many of the early studies were confined to in-vehicle noise and vibration assessments, development of appropriate criteria and development of procedures for improving the design of vehicles, waystructures and track to control the vehicle interior noise and ride quality. Similar importance was placed on control of noise in new station facilities, resulting in application of acoustical absorption materials both to control noise in the stations and to improve intelligibility of public address systems.

The technology and design procedures for control of in-vehicle noise and ride quality had a long history of development prior to the startup of the new system designs in the 1960's and 70's. This background coupled with the results of the various interior noise and ride quality studies commissioned by the new systems for identifying the best practices resulted in a relatively well defined set of criteria, design procedures, technology and materials for control of car interior noise and ride quality. Control of noise and reverberation in stations was also studied and then included on architectural design.

However, rail fixation technology was relatively poorly developed and, in many cases, traditional ballast and sleeper track or wood sleepers cast-in-concrete were still considered the primary design choice because of the long experience and known characteristics. There was limited experience with ballastless resilient rail fixation and floating slab track so these were considered unproved technology, viewed with caution and required both persuasion and demonstration of their potential to induce adoption.

The many studies which showed potential benefit to noise and vibration control, and which demonstrated operational safety and potential for reduced maintenance costs did result in adoption of resilient rail fixation. Further development followed including the light weight undamped floating slab concept. This presentation is a review of the designs developed and implemented for reduction of ground and structure-borne noise from the rail systems and the control of wayside airborne noise from surface and viaduct guideways.

Following the initial successes with the then new rail fixation technology, the work on development of improved and more effective noise and vibration control technology for the rail systems continued throughout the 1980's and 90's. In some cases this was a continuing effort to reduce costs and/or improve performance. However, it was also due to the imposition of more and more restrictive wayside noise and vibration requirements. Generally the same car interior noise and station platform noise criteria as were developed early on continue to be used. But as more and more cities or jurisdictions adopted restrictive environmental controls it has become an increasing requirement that new rail transit systems provide extensive vibration and noise control. One of the most graphic examples is the requirement for very low wayside noise and vibration by the Hong Kong Environmental Protection Department, EPD, as part of its overall program to reduce future outdoor noise levels in one of the noisiest cities in the world.

Track Fixation Developments

In evaluating and developing new or existing technology regarding the noise and vibration generated, it is extremely important that all aspects contributing to the noise and vibration be considered. There are numerous instances in the literature presenting glowing results which were in fact due to change of two or multiple parameters rather than the item being studied or evaluated. For example, considering the wayside noise from trains operating on at-grade or viaduct guideway, the principle noise sources are the propulsion system, including the motors and gearing, the wheel/rail system and auxiliary equipment such as air conditioners. At higher speeds, the propulsion system noise usually predominates, unless the wheels and rail are in poor condition. At medium speeds the wheel/rail noise usually predominates, but may be affected by auxiliary equipment noise. At low speeds or stopped, the auxiliary equipment noise dominates. Application of mechanical service brakes can also result in dominant noise. Thus, all of these factors must be considered when assessing the wayside noise.

Factors which affect the structure-radiated noise from a viaduct or the groundborne noise and vibration from at-grade and subway installations are primarily the guideway deck and girder construction, the rail fixation system and the dynamics of the vehicle bogie, principally the unsprung weight and the primary suspension resonance frequency. In several instances a change in the bogie dynamics resulted in erroneous evaluation of the effect of rail fastener changes which were being evaluated because the bogie dynamics change created a larger more dominant effect. Evaluation of the rail fastener performance without knowledge or recognition of the bogie change resulted in erroneous conclusions.

The high ranking of noise and vibration as an operational problem did result in the three new U.S. systems and the Toronto system commissioning studies intended to extend the existing knowledge and develop new technology for reduction of ground and structure-borne noise and vibration. The objectives of the studies included developing appropriate acceptability criteria. Feasibility and installation costs were also items of substantial concern.

One of the significant factors at the time was the success of the TTC system introducing resilient direct fixation in place of the conventional ballast and sleeper track or wood sleepers cast in concrete as used in subways built in the 1920's and 30's. The original motivation for the TTC introduction of resilient direct fixation rail fastener on concrete trackbed was to increase durability and life of the rail installation. The improvement in noise and vibration performance was an unexpected benefit.

In addition to the studies and research projects commissioned by the three U.S. projects, the Paris Metro extensive research program on direct fixation rail fasteners, resiliently supported ties (STEDEF system) and floating track slab as a means for reduction of wayside noise and vibration from subways provided valuable data and insights. Paris Metro also had a parallel program of refurbishing old subway lines via changing from steel wheels to pneumatic rubber tires as a means to improve the overall noise and vibration performance and other operational aspects. Although marketed in other countries as a quiet system, the pneumatic rubber tire system was never adopted by Paris Metro as a feature for new installations, and was used only for renovation of older subways.

One of the studies initiated by the BRRT was an evaluation of pneumatic rubber tire systems compared to steel wheel and rail to determine whether or not there was sufficient noise and vibration benefit to justify adoption of pneumatic rubber tire rather than steel wheel technology. The evaluation included the Transit Expressway vehicles on a test track in Pittsburgh, Pennsylvania and the Paris Metro rubber tired lines. The result of the study was the finding that, when compared on an equal train speed and equal passenger carrying capacity, the rubber tire system created the same or greater noise levels in the vehicle and at the wayside for surface guideways. The only benefit was reduced groundborne vibration and noise. It was concluded that in fact well maintained steel wheel and rail systems were potentially quieter with regard to airborne noise than can be expected for a pneumatic rubber tire system for equal operating conditions.

Much of the early work on development of rail fixation methods which would reduce the noise and vibration compared to either standard ballast and tie track or wood sleepers embedded in concrete, as used for most systems installed prior to the 1960's, was concentrated on the development of resilient rail fixation fasteners (baseplates). As part of its technology development program, the San Francisco BART system during the design development period constructed a test track and obtained three "laboratory" cars for assessment of various aspects of the transit technology, including noise and vibration. The test track included ballast and tie and viaduct with concrete girders and decks.

Figure 1 presents drawings of the three basic types of resilient rail fasteners used for fixing the rail directly to concrete roadbed with a low profile device: (1) the unbonded elastomer pad under a flat rail baseplate, (2) the bonded assembly with flat top and bottom plates and (3) the elliptical shaped bonded fastener with elastomer in shear rather than compression. The first type with unbonded flat elastomer was the type used in Toronto, and was the type investigated during the Paris Metro testing. Early experience showed the need for steel springs at the anchor bolts to prevent fatigue failure of the bolts. To eliminate the need for anchor bolt springs, the bonded fastener configuration evolved and a number of this type were included in the BART test track evaluations. There were many versions of the unbonded and bonded types of rail fasteners that were developed and which were evaluated for noise and vibration characteristics, both wayside noise and structure-borne noise. Figure 2 is a photograph showing the experimental setup for measuring wayside noise and ground vibration at the BART test track in 1966.

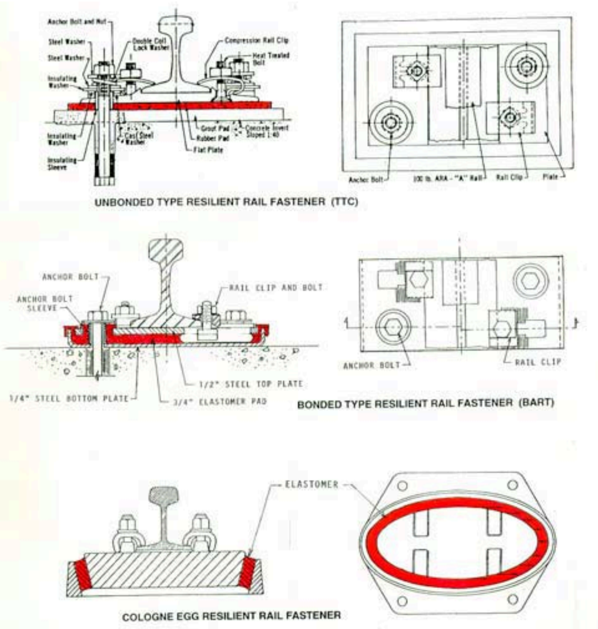

Figure 1 Three basic types of resilient direct fixation rail fasteners, unbonded, bonded and Cologne Egg

Figure 2 Photo of BART Test Track concrete viaduct and trial sound barrier wall

The requirements for rail support safety and durability resulted in rejection of many configurations developed by various manufacturers. Many candidates that had promising noise and vibration performance failed the 3 or 5 million cycle alternating vertical and lateral load test imposed. Also, providing for limited lateral rail deflection reduced the vibration and noise control effectiveness, eliminating further submissions.

In addition to resilient rail fastenings, resilient wheels of various types have been one of the features considered for transit vehicles for reduction of noise and vibration. Figure 3 shows the main types of resilient wheels which have been considered and which were included in the testing at the BART test track. Note that the PCC type wheel is a super-resilient design which has been used since the 1930's on streetcars for general noise reduction, particularly reduction of wheel squeal noise. This was particularly important with streetcars because of the short radius curves. With modern rail transit systems, limiting the minimum radius to about 200-250 m avoids wheel squeal. Thus, there is little benefit from use of resilient wheels on heavy rail transit. In general, while there have been experimental installations, all of the modern rail transit systems use solid steel wheels or non-resilient aluminum centered wheels with steel tires. For heavy rail transit systems with shorter radius curves the wheel squeal is generally controlled using ring-dampers on the wheels rather than resilient wheels. In contrast, most modern light rail systems do have resilient wheels, not the PCC super-resilient type, but a resilient insert type such as the Bochum wheel.

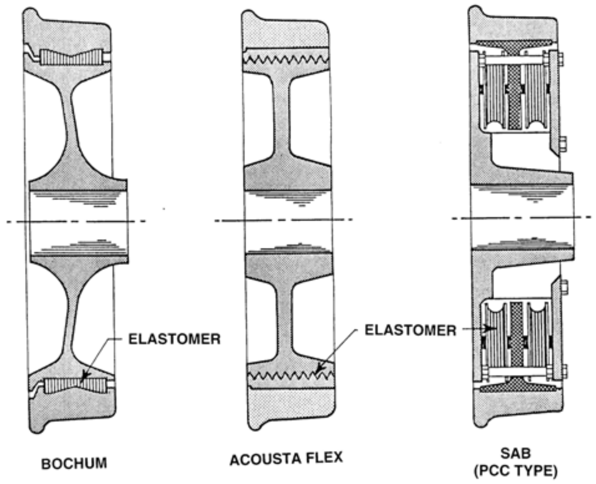

Figure 3 Three types of resilient wheels tested for application to rail transit

Because resilient wheels were one of the parameters being tested via the "laboratory" cars at the BART test track, many of the initial tests on the effectiveness of different types of resilient rail fasteners were inconclusive and in fact incorrect. This occurred because the particular laboratory vehicle used for all of the initial rail fastener tests at the concrete aerial structure was equipped at the time with the SAB (PCC) type resilient wheels. This wheel had resilience that was far greater than that of any of the rail fasteners, resulting in the measurements showing essentially no difference regardless of the stiffness or other characteristics of the rail fastener. The result of this evaluation was selection of a relatively stiff resilient fastener, about 75 kN/mm for the BART viaduct and subway installations. When later tests with standard steel wheels revealed the error in the early conclusions, the result was identification that a rail fastener stiffness in the range of 17 to 22 kN/mm was about the optimum compromise between maintenance of rail stability and minimizing structure-borne noise radiated from viaduct or transmitted from subways.

At the BART system concrete viaducts, the stiff fastener did result in some low frequency noise radiated from the structure but it was barely audible and did not increase the total A-weighted wayside noise level from the trains. Systems constructed later have used the softer fasteners with the result that there is lower radiation of noise from the viaduct structures and use of sound barrier walls is more effective in controlling wayside noise.

Figure 4 BART concrete viaduct with sound barrier wall

Most of the noise control provisions of the initial 112 kilometer BART system were concentrated on control of noise at the vehicle via specified maximum noise levels for the propulsion system and auxiliary equipment and because wayside noise was not considered an important parameter beyond the provisions of continuous welded rail and concrete aerial structure. There was only one small section of sound barrier wall. Figure 4 is a photo showing the sound barrier wall applied to the BART viaduct, a modification which resulted in about 6 dBA reduction of wayside noise.

The Metropolitan Atlanta Rapid Transit, MARTA, system followed the design of the three earlier U.S. systems and as a result incorporated more of the provisions for control of noise and vibration. Figure 5 is a photo of a MARTA steel girder and concrete deck aerial structure on which the softer variety of rail fasteners and the sound barrier wall were used extensively to reduce wayside noise from the viaducts. In this case, because the design requirements for safety walks on the outside edges of the viaduct deck made the deck much wider with resulting increased noise radiation, it was essential that the softer direct fixation fasteners be used in order to allow sound barrier walls to produce the expected noise reduction. Without the softer version of the rail fastener, the structural radiation from the MARTA aerial structure would have been a dominant source of noise. Constrained layer damping was used on the steel girders to give approximately the same noise radiation as for concrete girders along noise sensitive sections of trackway, including all sections with sound barrier wall. At locations where the viaduct girders do not have the constrained layer damping, there is significant noise radiation from the steel girders. The MARTA sound barriers provided 8-9 dBA reduction of wayside noise.

Figure 5 MARTA double track concrete deck with damped steel girder and sound barrier wall

There has been continuing development of new configurations and versions of the resilient rail fasteners. The major variation from the flat plate rail fasteners, as shown on Figure 1, was the introduction in about 1979 of the elliptical-shaped "Cologne Egg" fastener which places the elastomer in shear for vertical load and compression for lateral loads. This allows for a much softer rail support while maintaining the rail stability required for safe operation of the rail vehicles. The Cologne Egg type fasteners can have a vertical stiffness in the range of 9 to 13 kN/mm, which is of significant benefit in reducing structure-borne radiation from viaduct structures with steel girder and in reduction of groundborne vibration and noise from subway or at-grade rail installations.

The basic limitations on rail support lateral stiffness and/or rail lateral deflections limit the lower range of stiffness which can be achieved with the flat plate type of rail fastener, either the bonded or non-bonded configuration. Thus, there is a practical limit to the reduction of groundborne noise and vibration from at-grade and subway installations of flat plate type of rail fasteners. As it turns out, the minimum practical stiffness results in groundborne vibration and noise similar to that resulting from ballast and tie track. Because of the characteristics of the Cologne Egg type fastener, the result is a reduction by 6 to 8 dB of the groundborne vibration and noise for frequencies above about 40 Hz. In many cases, this is sufficient to achieve satisfactory results, particularly for new rail facilities placed adjacent to non-noise-sensitive land uses.

An alternative design which also provides about 6-8 dB greater reduction of groundborne noise for frequencies above about 40-50 Hz is the resiliently supported or booted double tie. This is the STEDEF design which was included in the early Paris Metro studies and has been used at some locations where the additional reduction was considered adequate, particularly before the Cologne Egg gained acceptance. The resilient double tie system, now called Low Vibration Track, is not low profile, requiring a second pour of concrete to embed the ties, but does have the advantage of reduced radiation of airborne noise from the rail because of the stiff fixation to the concrete tie mass.

Floating Slab Track

There are may instances where the control of ground and structure-borne noise levels achieved by resilient rail fasteners, or the alternative Cologne Egg or Low Vibration Track, are not low enough for satisfactory or acceptable results. Adjacent land uses which are noise sensitive, such as residential, school or performing arts facilities, and in some cases even commercial facilities such as office or court buildings may require a higher degree of noise reduction. In these instances the practical alternative is a fully vibration isolated or floating track slab design.

As a part of the noise and vibration assessments performed for the new U.S. transit systems, measurements were made of the groundborne noise and vibration at various locations in buildings near the existing subways in Toronto and at other existing transit systems such as those in Philadelphia and Chicago. Further, information from the Paris Metro and other studies in the literature were used along with the measurement results to develop a basis for projecting the expected groundborne noise at locations along the Washington, D.C. Metro routes to determine whether or not mitigation was needed. This same procedure was used for subsequent evaluations and projections with a continuing growth of the database as new systems went into operation providing opportunities for additional measurements.

The initial assessments indicated several locations along the WMATA route where mitigation beyond that which could be provided with resilient rail fasteners was necessary. Initially, the planners and consultants for the system thought that a floating slab track type of mitigation would be needed at stations, but not in other locations. An objective analysis showed that there were many locations requiring added mitigation but only a few instances where track through stations needed the mitigation.

Identifying the need for mitigation at the WMATA system subways motivated the development of the initial light weight loading slab configuration. There had previously been a successful floating slab type of installation at the Barbican Scheme site in the City of London where residential development, an Arts Center and several buildings sensitive to noise were located close to an underground railway. When the railway was realigned, a slab bridge deck type of design was developed, a design which required substantial increase in depth of the subway tunnel, along with the installation of a complex system of crossbeams on rubber bearings under the ends of 10 m length concrete bridge decks with a damping layer and ballasted track on top. The design incorporated lateral bearings for lateral restraint without reduction of the isolation affect. The stiffness of the natural rubber bearings was tuned to about 6 Hz, considering the mass of the bridge deck and the ballasted track. A similar system was installed some years lateral on the London Heathrow transit line. This type of design was very complex and expensive so that there was strong motivation to develop an alternative design which would be effective and of much lower cost, including minimum depth to minimize additional cost in excavating the subway tunnel.

One of the factors which had discouraged prior development of a light weight floating track slab system was the perception that damping was needed to prevent amplification of the wheel/rail interface vibration forces at the natural frequency of the floating slab on the resilient bearings. The Barbican and Heathrow slabs had heavy damping layers in addition to the ballast to accomplish damping of the floating track assembly.

After an analysis of the type of forces applied by a moving rail vehicle to the trackbed and the supporting structure, it was identified that the forces are random impact-like forces and moving or non-stationary relative to the support system. Therefore, it was concluded that the response would be more similar to the response of a spring mass system to an impulse or impact force than that due to steady-state excitation, which is the more familiar type of analysis. This conclusion led to the estimate of 2 to 3 dB amplification factor for a lightly damped floating slab track system rather than the 15 to 20 dB amplification that would be expected for steady-state excitation of the same system.

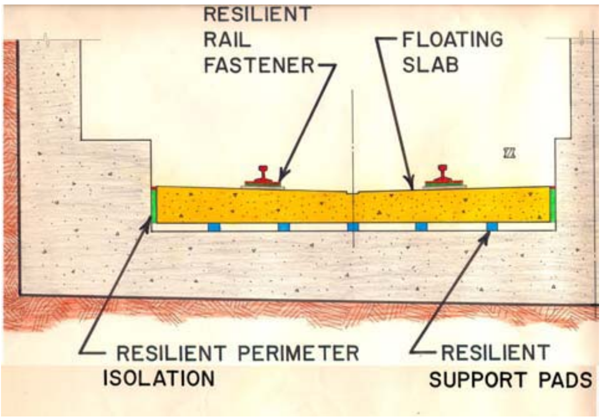

Figure 6 Cross-section of continuous floating slab design developed for WMATA

Figure 6 presents a cross-section of the light weight floating slab design developed from the analysis which indicated that the moving random excitation would create the effect of a damped single-degree-of-freedom system. For the WMATA system continuous cast-in-place floating slabs using a sheet metal form or shutter left in place were constructed. Stationary steady-state tests of an initial installation did indicate an amplification factor of 15 to 17 dB at the design resonance frequency, but that for frequencies of concern in the groundborne noise there was substantial reduction.

This design did achieve the goal of low profile while retaining enough mass to achieve the 15 to 20 dB of groundborne noise reduction needed at some locations. The added depth for box-section tunnels was small, 300 mm, and the design was adaptable to round tunnels without increasing the tunnel diameter.

A significant part of the development of the design was the determination of the appropriate elastomer for the floating slab. To this end there were several requirements that limited the design. One was an imposed limit of 3 mm for rail deflection. Another was a limit of 300 mm for the total depth of the slab and resilient pads, at least for the initial installations. A third limit was the need to have natural frequency low enough to provide the groundborne noise reduction required and low enough to avoid interaction with the vehicle bogie primarily resonance frequency. These requirements taken together indicated that natural rubber was the best selection for the elastomer. With natural rubber the ratio of dynamic-to-static stiffness is the minimum, allowing for a ratio less than 1.4. Most synthetic elastomers, including Neoprene, have a ratio of 2.0 to 2.5, resulting in substantially greater rail deflection for a given resonance frequency. Natural rubber was also known and demonstrated to have a long service life and can be formulated to have very low creep under compressive load.

Through correspondence in 1972 with the Malaysian Rubber Bureau in the U.K., a formulation specifically tailored for floating slab track was developed and has subsequently been used as the specified elastomer with great success. Some of the earliest installations have been in service for nearly 30 years and show no signs of deterioration or change in mechanical properties. There are many older installations of natural rubber bearings used for vibration isolation applications or other purposes which demonstrate the expectation of very long life. One of the oldest is the Victorian Railway's viaduct between the Flinders Street and Spencer Street Stations in Melbourne where the installation completed in 1891 is still in service. The rubber isolation pads between the viaduct structure and the supporting piers are still in excellent condition and functioning to minimize vibration transmitted from the trains to the stone and brick piers.

With the selection of elastomer, the design of the WMATA floating slabs was determined, including the decision to cast-in-situ continuous slabs with pinned moment connections between individual sections as the concrete was poured. While these floating slabs were successful in reducing the groundborne noise and vibration, they also radiated airborne noise due to bending waves in the continuous slabs. For standard track the low frequency radiated noise was a barely noticeable addition to the noise generated by the train propulsion equipment. However, at special trackwork, the noise was thunderous, audible in the cars and at station platforms where a crossover was located near the station. The main problem encountered was that for some sections the contractors were allowed to substitute polyurethane elastomer pads for the natural rubber pads. The polyurethane pads turned out to be hydroscopic and lost their mechanical stiffness when exposed to water. The failed pads had to be replaced, a process which was difficult and expensive due to the continuous poured-in-place slab configuration.

In 1974 the TTC opened a new Yonge Street Extension with only the resilient rail fasteners for mitigation. This line went further into residential areas than previous lines and resulted in a huge amount of complaints about groundborne noise and vibration. This led to extensive research and development programs both to improve the existing new line and to identify better mitigation for future new subway lines. One of the TTC track engineers proposed precast concrete sections as a lower cost alternative to the continuous floating slab. The configuration proposed also provided for access and easy replacement of the isolation pads. With revisions to optimize the acoustical performance, the design was developed into what is known as the double-tie or discontinuous floating slab track.

Figure 7 is a plan view showing the typical 1.5 m length segments for the floating slab. The side pads and end pads provide for complete isolation with mechanical retention and to accommodate lateral loadings. Figure 8 is a photo of the double-tie floating slab system before installation of the rail fasteners and rail. This configuration essentially eliminates the airborne noise radiated from the slab as an addition to train noise heard by the patrons, provided that the resilient rail fastener has sufficient resilience to control transmission of higher frequency vibration from the rail to the slab. At the TTC system, the noise radiated from the slabs is at or below the train noise level at the same frequencies and is not noticeable either on station platforms or in the cars. At some other more recent installations where the rail fastening is too stiff, there is noticeable noise radiation from the slabs. In one instance, the rail was fastened directly to the slabs, resulting in very high noise level radiated into the cars and very poor groundborne noise control performance.

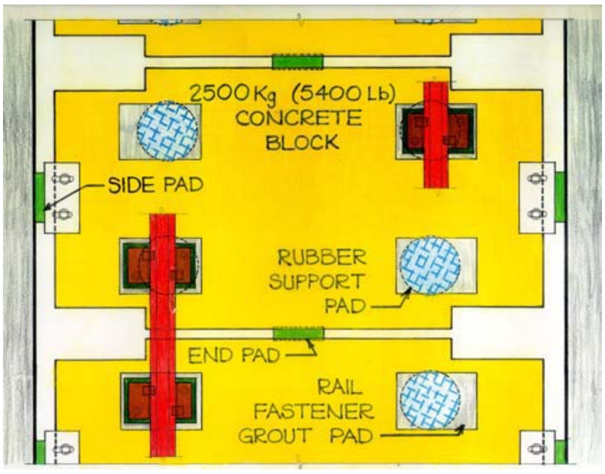

Figure 7 TTC double-tie discontinuous floating slab design - 1500 mm length precast concrete blocks

Figure 8 Photo of TTC double-tie system in subway - before installation of the rail fasteners and rail.

The earliest installations in Toronto, with the natural rubber bearing pads as specified, have now been in service for 28 years without any evidence of deterioration of the rubber pads. Further, there has been no added or special maintenance required or created by the floating slabs. The success of the design has led to the adoption by a number of rail transit facilities where mitigation of groundborne noise has been necessary. These include the MARTA system in Atlanta and the transit facilities in Los Angeles, Buffalo and recent extensions of the BART system. Other notable applications are at the Hong Kong Mass Transit Railway and at the Canary Wharf in London, U.K.

Another early installation of the double tie concept floating slab was at the Melbourne Underground Loop, MURLA, subway. The four lines of the Loop are in close proximity to a number of noise sensitive facilities. Therefore, an extensive study was completed by Victorian Railways over the period from 1973 through 1978. This study included a trial installation at the Jolimont Cutting to provide in-service testing and evaluation of the proposed floating slab track system. While the intermediate mitigation of resilient booted tie system would have been adequate at some locations, it was not adequate at others. To avoid the complication of multiple transitions and multiple types of trackwork to be maintained, it was determined the entire Loop network would be the double-tie floating slab. The system was completed and opened in 1981.

Recent Developments

The new extensions of the Hong Kong MTRC and the new line constructed for the Kowloon Canton Railway Corporation, KCRC, have required creative combinations of structure-borne noise control and sound barrier technology. The environmental requirements for these new facilities are among the most restrictive in the world. At first it was thought that achieving the design goal of 64 dBA at 25 m for a train at 140 km/hr would require a covered viaduct with floating slab track. However, using the floating slab track design principles developed and refined from experience with each new system combined with a new approach to sound barrier wall design enabled creating an overall design achieving the low wayside noise level without a complete cover over the guideway.

The overall design approach for the 21 km KCRC viaduct was the use of concrete guideway and girders, floating slab track to minimize structure-borne noise radiation from the guideway and integral sound barriers, soft rail fasteners to minimize noise radiation from the floating track slabs, sound barrier walls with sound absorption and an undercar/under-walkway sound absorptive plenum to supplement the sound barrier walls. The overall design also required low noise performance for the vehicle propulsion and auxiliary equipment. For example, a typical roof-mounted air conditioner could by itself exceed the overall wayside noise allowance, since the AC unit noise would not be mitigated by a sound barrier wall.

Figure 9 is a representation of the KCRC viaduct final design showing the elements included for control of wayside noise, the all-concrete structure, the floating slab track, the sound barrier wall with absorption and the under-walkway plenum with absorption to minimize noise transmitted to the walkway-to-car gap to the sound barrier wall and thence to the wayside. Figure 10 is a photo of the completed viaduct and Figure 11 is a close-up photo showing the floating slab segments with the soft Cologne Egg type rail fastener. Trains began running on this facility in 2004 and the wayside noise measured was 64 dBA L_{eqmax} at 25 m for an 8-car train at 140 km/hr.

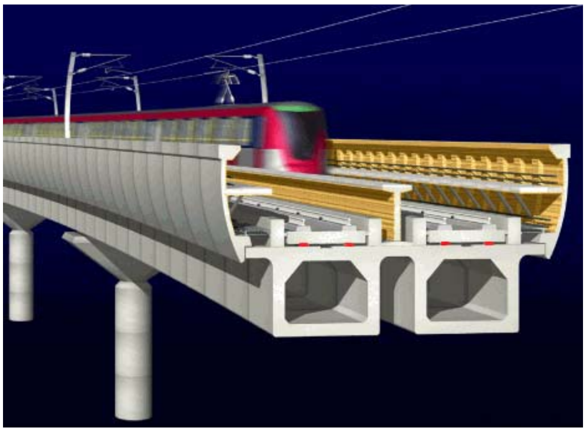

Figure 9 KCRC viaduct with floating slab track, absorptive sound barrier wall and under walkway absorptive plenum

Figure 10 Photo of KCRC viaduct completed

The fact that the new KCRC viaduct was designed and constructed to successfully control the wayside noise without need for complete cover over the trackway demonstrates that the principles, procedures and materials which have been developed do accomplish the acoustical design goals. The design represented in Figure 9 was based entirely on empirical and analytical design analysis without construction of a test track or test section to demonstrate the performance.

Figure 11 Close-up view of KCRC viaduct floating slabs with low stiffness rail fasteners

Summary

Through the application of simple vibration isolation design principles with careful attention to the entire complex system affected by individual noise and vibration control features, it has been found possible to greatly reduce both the wayside airborne noise from viaduct structures and the groundborne noise and vibration from subway and at-grade rail installations. The principles applied to viaducts can also, of course, be applied to bridges. With attention to the design factors which affect structure-radiated noise, it has been possible to reduce the unmitigated wayside noise from the range of 84 to 87 L_{Aeqmax} at 15 m for 130 km/hr train on a concrete viaduct structure to 65-67 L_{Aeqmax} for the same conditions but with mitigation.

Through development of light weight, undamped floating slab systems which take into account the vehicle bogie dynamics, the trackway or subway structure mass and the surrounding geology characteristics, it is now possible to install new rail systems in very close proximity to noise sensitive land uses without the impact of low frequency rumbling noise which has traditionally been associated with rail system subway trains. For example, initial operations of the TTC Spadina line, which opened in 1978, resulted in complaints from only two houses and it turned out these were due to problems with flat wheels during the initial operations. After the flat wheel problems were corrected, there were no further complaints and it was reported that trains in a tunnel only 3 m from houses were only occasionally audible.

With the technology and materials now available for rail system noise and vibration control, it is possible to install new facilities in locations or along alignments which in the past would have been considered unfavorable because of the noise and vibration impacts. Even with the more restrictive standards now imposed by many jurisdictions, the transit system planners and designers have less limitations regarding selection of alignments for new transit facilities. Of course, there still remains the problem of convincing the neighbors of a potential new facility that the wayside noise and vibration will be satisfactory and acceptable in the community.

References

[1] "Comparison of Noise and Vibration Levels in Rapid Transit Vehicle Systems", NCTA Technical Report, by Operations Research Incorporated, April 1964.

[2] Allen, P. W., Lindley, P.B. and Payne, A. R., "Use of Rubber in Engineering", Proceedings of a Conference held at Imperial College of Science and Technology, London, 1966.

[3] "Aerial Structure Noise and Vibration Measurements", Technical Report prepared by Wilson, Ihrig & Associates, Inc., October 1966.

[4] "Diablo Test Track Noise and Vibration Measurements, Technical Report prepared by Wilson, Ihrig & Associates, Inc., June 1967.

[5] "San Francisco Bay Area Rapid Transit District Demonstration Project Technical Report Number 8 - Acoustic Studies", prepared by Parsons Brinckerhoff-Tudor-Bechtel, June 1968.

[6] Colombaud, J. L., "Noise and vibration levels suit ballastless track for underground railways", Rail Engineering International Conference, June 1973.

[7] "Noise and Vibration Design Criteria and Recommendations, Baltimore Region Rapid Transit System", prepared by Wilson, Ihrig & Associates, Inc., February 1974.

[8] Transportation Systems Center General Brochure, prepared by Transportation System Center, 1977.

[9] Lawrence, S.T., Toronto's Double Tie Trackbed System, American Public Transit Association Rapid Transit Conference, Chicago, IL, 5-8 June 1978.

[10] "Guidelines for Design of Rapid Transit Facilities", prepared by Rail Transit Committee, American Public Transit Association, January. 1979.

[11] Lutz, R., "Survey of the work by ORE about Railway Noise", contributed paper to Third International Workshop on Railway and Tracked Transit System Noise, Monument/Pueblo, Colorado, 8-10 April 1981.

[12] "Toronto Subway System Track Vibration Isolation System (Double Tie)" Technical Report, Toronto Transit Commission Engineering Department, June 1982.