Rail Transit Noise and Vibration Impacts – Why Environmental Planning Doesn't Always Work

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ABSTRACT

Rail based transportation systems produce noise and vibration that can cause annoyance or problems in the community without application of appropriate mitigation. Standards and recommended criteria have been developed to control the levels of noise and vibration to minimize impact on the nearby community. Unfortunately unanticipated community complaints of excessive noise and vibration still arise after system start-up or modifications. Practical experience has shown that many of these complaints have merit and that they are usually caused by unforeseen technical or administrative reasons. A review of some of these cases at different rail transit properties in the United States indicates that although resolution is most often achieved, the process may take considerable resources and time.

INTRODUCTION

With the increase in population in and around metropolitan cities, the need for efficient transportation systems has increased over time. Rail based transportation systems have been embraced by more and more cities. Although the United States and Canada had, at one time, extensive rail "trolley" systems and interurban rail systems everywhere, most of these systems were abandoned by the 1940's and 1950's with the advent of improved roads and automobile expressways. Fortunately, there were some cities which retained these systems as was done throughout most of Europe.

Today, existing lines are being extended, while new rail systems are proposed for many metropolitan cities due to congestion, air pollution, the high cost of gasoline, etc. For classification purposes, rail systems for passenger transport fall into three basic categories:

1. Conventional and high speed railways in urban areas, generally operating on or adjacent to existing railroad rights-of-way.
2. "Heavy" rail transit in high density cities with substantial portions in underground subways.
3. "Light" rail transit in medium to high density cities and metropolitan areas with substantial portions located at grade or in city streets.

Another category which encompasses all three of the previously identified categories includes railway yards/maintenance facilities and transit stations which may generate an entirely different set of environmental problems than the operation of trains along the tracks.

With respect to noise and vibration generation there are at least three ways that noise and vibration problems can occur: 1) introducing a new line into a community or neighbourhood, 2) the neighbourhood expands adjacent to existing facilities, and 3) changes in operations on existing facilities. Since these conditions can create significant impact on people living or working near the transit facilities, a number of environmental standards, recommendations and assessment procedures have been developed to minimize this impact and assist in the development of feasible mitigation measures.

The character of noise from trains operating at-grade or on aerial structure is different than the character of noise which arises from trains operating underground in subway. The noise from trains operating at-grade or on aerial structure is *airborne* and can be perceived by individuals outside of a building or inside of a building at an attenuated level after the noise has passed through the windows, doors or walls of the building. The noise from trains operating in subway is *groundborne* and can be perceived only when an individual is inside a building near the subway. Outdoors groundborne noise is inaudible. A train operating in subway creates vibration at the wheel/rail interface which is transmitted to the subway structure, to the ground and then through the ground to a building structure where it is then radiated in the form of a low-frequency noise which can be heard and sometimes felt as mechanical vibration inside buildings near the subway. Trains operating on aerial structure will produce vibration levels in the ground which are generally low enough in level that they will not be reradiated as an audible noise or felt by occupants of adjacent buildings, while the vibration levels produced by trains operating in subway or at-grade can in some situations be high enough in level that they can be felt by occupants of nearby buildings or affect very vibration sensitive laboratory-type equipment. As for groundborne noise, vibration from train operations can only cause impact to people or special equipment inside buildings. In the author's experience, groundborne vibration is always below the level necessary to cause even minor structural damage to buildings.

In this paper, relevant standards and recommended criteria applicable in the United States are discussed along with situations where community complaints arose despite the application of mitigation measures that were ostensibly designed to minimize noise and vibration impacts.

STANDARDS AND RECOMMENDED CRITERIA

Before discussing some particular situations where community complaints arose despite environmental planning, a discussion of the standards and recommended criteria which are used in the United States is in order. As previously indicated, there are at least three ways that noise and vibration problems can affect a community: 1) a new rail transit line is constructed in the neighbourhood, 2) the neighbourhood expands adjacent to existing facilities, and 3) there are operational changes at exiting facilities. There are different standards which can apply to each of these situations. However, the standards and recommended criteria for each of these situations can be divided into two basic types: those that are based on an absolute limit and those that are based on a relative limit. The absolute limit is generally based on L_{max} or on some upper limit of L_{eq} or L_{dn}. Relative limits are almost always based on an increase in hourly L_{eq} or in L_{dn}. The use of appropriate absolute standards first developed in the 1970's has been shown to be very successful over the years, while relative standards can be less successful if not applied appropriately or if assumptions regarding train operations or existing environmental noise levels are ultimately incorrect.

In the United States, some of the standards and recommended criteria have resulted from the implementation of the National Environmental Policy Act (*NEPA*, 1970) which established a national environmental policy and goals for protection, maintenance, and enhancement of the environment and provides a process for implementing these goals within federal agencies. Although the Act produced a general document which applies to many areas other than noise, it sets the framework for what various agencies must do in order to achieve the goals of the Act. The appropriate federal agency for rail transit is the Department of Transportation, Federal Transit Administration.

Other standards and regulations have resulted from requirements at the state and local (city) level. Of note is the California Environmental Quality Act (*CEQA*, 1970) which has the basic goal to develop and maintain a high-quality environment now and in the future, with specific goals for California's public agencies to: 1) identify the significant environmental effects of their actions; and, either 2) avoid those significant environmental effects, where feasible; or 3) mitigate those significant environmental effects, where feasible. CEQA is noted, as it is a very comprehensive document, which includes a checklist for identifying noise and vibration issues, and it is applicable to the state, which is geographically far from the population centres of the east coast of the United States, but has the largest population of any state (over 37 million). CEQA has also been the model for environmental regulations in other states. Without getting into details, the requirements of CEQA are different than those of NEPA, but in California, if federal money is involved in a project, which is typical of a rail transit project, then both a CEQA and a NEPA analysis is required.

Standards or guidelines for rail transit noise have been formulated by an industry group, the Institute for Rapid Transit (*IRT*, 1973), which has been updated by the successor group, the American Public Transit Association (*APTA*, 1979 & 1981), which is now known as the American Public Transportation Association. The Federal Transit Administration has developed recommended criteria in *Transit Noise and Vibration Impact Assessment*, (*HMMH*, 1995) which has been updated (*HMMH*, 2006). This document is commonly known as the FTA Guidance Manual.

The APTA Guidelines are based on absolute limits (L_{max}) for train passby frequency typical of most systems with the specific noise limits based on the type of community along the transit corridor (i.e., low density, average, commercial, etc.). Although the time constant for the sound level meter is not specified (i.e. fast or slow meter response), the limit essentially refers to the typical maximum noise level during the passby of the train, which for most passbys is more than 1 second in duration so that the meter time constant used for such measurements should not make a significant difference. The APTA Guidelines also recommend limits for transit vehicle noise and noise within underground stations. The FTA recommended criteria for airborne noise are based on relative limits with respect to the existing noise exposure with the metric of $L_{eq}(h)$ for land uses where quiet is an essential element of their intended purpose and for institutional land uses with primarily daytime and evening use. L_{dn} is the metric for residences and for buildings where people normally sleep. Impact is characterized as "severe", "moderate" or "no" with greater increases in noise levels allowed where the ambient is currently low, with smaller allowances allowed where the ambient noise level is moderate or high. The FTA Guidance Manual also provides reference levels for various types of trains and related activities with adjustments for speed, length of train, type of guideway, etc.

The FTA Guidance Manual also provides recommended absolute criteria for groundborne noise and vibration, along with basic and more advanced methods for predicting and assessing groundborne vibration impact. The recommended criteria for groundborne noise are in terms of A-weighted noise levels. The recommended criteria for a general vibration assessment are in terms of a single-number RMS vibration velocity level, while the recommended criteria for a detailed vibration analysis are in terms of 1/3 octave band RMS vibration velocity levels. The detailed prediction procedures and many of the correction factors are based on the work of Nelson and Saurenman (Nelson, 1988).

Overall, the FTA Guidance Manual provides a basis for planners and acousticians to determine expected impact and the need for mitigation. Since most new transit systems and extensions for existing systems rely on some percentage of federal funding, the procedures and recommended criteria are used for impact assessment. Unfortunately the Manual is used by many who have little experience with rail transit systems and lack a basic understanding of acoustics and the intent of the criteria such that assumptions and the impact assessment can be incorrect. In addition, many who have used the Manual have failed to realize that both the procedures and criteria are *recommended* and that there is no substitute for experience with rail transit acoustics for particular situations.

SITUATIONS WHERE ENVIRONMENTAL PLANNING FAILED

As indicated there can be a number of reasons why environmental planning does not prevent community complaints. Even when the analysis and mitigation is appropriate, a community's false expectations can still cause complaints. Many times these are fuelled by statements that the system will be "noiseless", "generate noise no greater than a quiet car", etc. Obviously these statements are usually made by those who are unfamiliar with the operations of rail transit systems and the public has every right to be suspicious of such statements. However, there are other administrative or bureaucratic blunders that can cause legitimate complaints that may not be known until a new system begins operations or new equipment becomes an integral part of the system. Problems can also arise even when there is a clear engineering solution for providing mitigation which may not be successful due to unusual and unexpected conditions, since, of necessity, the prediction of noise and vibration impacts are based on many seemingly reasonable assumptions.

A basic noise mitigation measure is the use of a sound barrier wall to reduce the noise from transit train operations. There are a number of situations where the wall was too short to be of benefit, or sound absorption material in the inside face was omitted such that the actual noise reduction was less than anticipated. However, an even more obvious problem arose on one project, where the civil stationing of the alignment was altered after the final environmental review. The fact that the civil stationing was changed by only a small amount negated the benefit of the barrier wall. This error happened many years ago and photographic evidence is no longer available. However, the contractor built the wall as specified, which left an approximate 3m gap between the end of the wall and where it abutted a transit facility building. The gap resulted in a short duration increase in the noise level with each passing train which was quite noticeable to the adjacent residential community. An investigation followed the community complaints, the problem quickly identified and solved with a barrier wall installed in the gap.

Although relatively expensive, one quite successful mitigation measure used for the reduction of groundborne vibration and noise is the use of a floating slab trackbed. The floating slab basically consists of a concrete slab supported on resilient elements, usually natural rubber or a similar elastomer. Figure 1 is a schematic representation of the floating slab trackbed. They are generally used where low frequency (<30 Hz) vibration reduction is needed. Using a combination of slab thickness, resilient support pad size and physical characteristics, a design with a particular resonance frequency can be designed such that the reduction begins (in theory) at √2 times the resonance frequency.

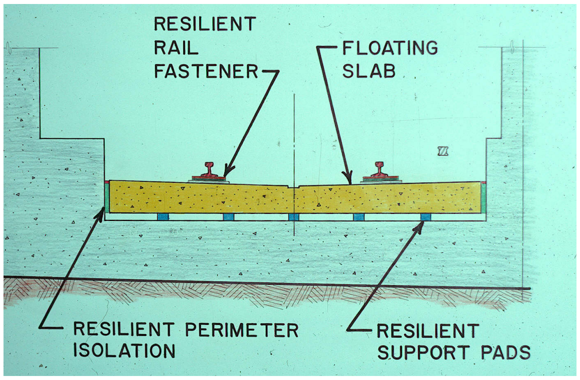

Figure 1. Schematic Drawing of Floating Slab Trackbed

Although floating the floating slab trackbed has been most often installed in subway tunnels, it has also been successfully installed at-grade and for street running of light rail trains. Figure 2 shows an installation in a U-wall section at the Bay Area Rapid Transit (BART) system in the San Francisco Bay Area.

Figure 2. Floating Slab Trackbed at BART

As indicated, the floating slab trackbed can be very effective at reducing groundborne vibration, if designed correctly considering the primary suspension characteristics of the transit vehicles, the characteristics of the intervening soil between the transit structure and the adjacent building and the specific building characteristics. At one heavy rail system, the underground subway tunnel was proposed to go directly beneath an apartment complex. It was determined that a floating slab trackbed would mitigate the groundborne vibration and noise to acceptable levels. This determination was made several years before the construction of the subway tunnel. In that period of time when the environmental review determined that a floating slab trackbed would be necessary and the engineering design completed, the apartment complex was demolished and a parking lot was built in its place. Since the requirements for the floating slab trackbed were incorporated into the contract for construction, the floating slab trackbed was built, as there was no final confirmation of the need for mitigation prior to construction, and thus there is now a floating slab beneath the parking lot with no benefit plus the additional expense necessary for its implementation.

Floating Slab Coincidence Effects

Although the basic insertion loss from the use of a floating slab trackbed is a function of the parameters previously indicated, these parameters can be very critical. The design of an 8-10 Hz floating slab will result in significant differences in wayside groundborne vibration and noise when compared with a 16 Hz floating slab, depending on the particular parameters of the transit vehicle, soils and type of structure. The need to try and quantify each of these parameters prior to finalizing a design can be very critical.

One situation involved a heavy rail system which first opened for service in the 1970's. Environmental planning indicated the need for a floating slab trackbed at several locations, primarily for the reduction of groundborne noise. During that time period, there was very little experience with the optimization of these parameters and the effect that each would have on the success of the design. Previous experience with other systems had shown that the floating slab trackbed was very successful and there was no reason to believe that this would not be the case at this system.

The original alignment design had the transit station located along an existing railroad alignment. However, it was decided that having an underground subway station in the centre of the city would increase its use and make it more accessible to most passengers. Thus the alignment was designed such that it was relatively shallow, and a cut and cover design was utilized, which put the edge of the tunnel within approximately 5 m of the foundation of the nearest residence. Although there was some doubt about achieving the project groundborne noise criterion for the nearest residences, a decision was made to maintain the shallow depth of the tunnel due primarily to cost considerations. A deeper tunnel would increase costs substantially. A floating slab trackbed was designed with a relatively high resonance frequency (14-16 Hz) since the concern was with groundborne noise.

When this portion of this system was designed in the 1970's, there were no specific groundborne vibration design criteria established for any modern rail transit system in the United States. At that time it was believed that distinct feelable vibration would not be of sufficient magnitude to be a significant problem, however, it was known that groundborne noise, radiated due to the groundborne vibration could be an issue in some circumstances. Following the commencement of pre-revenue and revenue service, there were complaints from local residents regarding excessive levels of vibration in their homes during train passbys. Field measurements confirmed that the vibration was distinctly perceptible. Additional mass was added to a portion of the floating slab trackbed in an attempt to reduce the resonance frequency of the floating slab and thereby reduce the resulting groundborne vibration. Although the reduction in groundborne vibration was measurable at that time, the resulting vibration from train operations was still in the feelable range in many of the nearest residences.

Figure 3 shows some of the affected dwellings as they look today. The underground subway is located below the street. Field measurements indicated that the vibration from train passbys as measured on the ground floor with a slab-on-grade foundation was generally below the level of feelability. However, identical vibration measurements in the upstairs main bedroom indicated that the levels were well above the level of feelability with a distinct sharp peak at 16 Hz. This indicates that there is substantial floor amplification inside the structure which is being excited at 16 Hz. On average, the increase in vibration velocity level from ground floor to second floor inside the building is typically greater than 15 dB. Slowing trains from the typical speed of 60 to 75 kph did not result in a significant reduction of vibration until the speed was too low to maintain reasonable operating conditions.

Figure 3. Residences adjacent to underground subway

Since the design of this portion of this transit system, much has been learned regarding the generation of groundborne vibration, and it is generally recognized that under certain conditions, distinctly feelable vibration is possible inside buildings adjacent to modern subway systems during train passbys. Consequently, specific groundborne or structure-borne vibration criteria have been developed and applied to new designs. As previously indicated, these criteria have been incorporated into the FTA Guidance Manual.

Since the design of the floating slab was to reduce groundborne noise, the relatively high resonance frequency was not considered a problem. However, the truck (bogie) of the new transit vehicle was designed with a relatively stiff primary suspension that used rubber bushings rather than a chevron type suspension. Although the primary suspension resonance natural frequency is not documented, the durometer of the rubber bushings is greater than 60 which effectively increases the unsprung mass. Based on a review of problems encountered in the 1970's and 1980's, it is clear that although this design of truck has been found to be reliable and require minimum maintenance, it is also a design which has contributed to high levels of wayside groundborne vibration at a number of transit properties and has generated high levels of vibration on the truck that is sufficient to loosen or damage truck mounted equipment. Although the problem was not entirely solved, softening of the primary suspension rubber bushing and procurement of transit vehicles with a truck design utilizing a chevron type primary suspension alleviated most of the complaints.

At the time of the original design, the interaction between the primary suspension of the vehicle, the design resonance frequency of the floating slab and the primary response frequency of suspended floors in buildings was not well understood. Now it is known that it is important not only to have a low resonance frequency primary suspension on the vehicle but also that the resonance frequency of the floating slab should generally be in the range of 10 to 12 Hz or less for good groundborne noise and vibration reduction at most transit systems.

After over 25 years of operations, complaints from residents in these some dwellings began to reappear. Unfortunately, the historical knowledge regarding the nature of this problem was not retained by the transit system and new vehicles were again procured with a stiff rubber bushing type primary suspension. In addition, maintenance issues such that trains with significant wheel flats were being operated typically increased the vibration levels. Extensive measurements in the tunnel, on the transit vehicle trucks, at the surface in the residences confirmed the increase in vibration over time. Since this is a relatively complicated problem, there is no simple solution. A combination of solutions will probably be implemented when possible. Among those are to run vehicles with trued wheels, soften the primary suspension bushings, grind the running rail to assist in minimizing the wheel/rail roughness which contributes to groundborne vibration, add additional weights to the floating slab trackbed to further reduce the resonance frequency, and stiffen the upper wooden floors of the affected residential structures to shift the resonance frequency of the floors from the 16 Hz region.

Transit Vehicle Procurement Specification Errors

Whenever rail transit vehicles are procured, detailed specifications are prepared to ensure that the vehicle will properly function on the system and serve the travelling public. In addition, both interior and wayside noise limits must be achieved, along with suitable ride quality. In the 1990's a rail transit property needed to acquire additional transit vehicles and eventually replace all of the vehicles in their fleet, most of which dated from the 1970's. A procurement specification was prepared which included interior noise control criteria and wayside noise control criteria. Although the specifications were ostensibly prepared by an outside consultant, the technical specifications were published and issued to potential suppliers by the transit agency.

Typically interior noise levels are measured at various locations within the vehicle with the results averaged. For wayside noise, the specification usually limits the maximum noise level for various conditions when measured at a distance of 15 m from track centreline. This procurement specification was printed using a two-column format similar to this text. Unfortunately when someone formatted the table of requirements for wayside noise, the heading for interior noise continued into the adjacent column such that the requirements for wayside noise were for an average noise level over a particular speed range. So rather than limiting the maximum noise level to 77 dBA at 15 m for a two-car train operating between 0 and 65 kph, the specification limited the average noise level to 77 dBA. For the successful car manufacturer, this was interpreted to mean that the L_{eq} for a two-car train operating between 0 and 65 kph could be no greater than 77 dBA at 15 m. This is a very different requirement than limiting the maximum noise to the same level of 77 dBA.

It is also advisable to have a pure-tone penalty in the specification. Most modern vehicle procurement specifications do contain a penalty for pure tone noise. Typically a penalty of 3 dBA is applied to noises which contain very strong and noticeable pure-tone components in order to account for the increased human perception of such a noise when using only a single number metric such as A-weighted noise levels. However, like the error involving the indication of average noise level rather than maximum noise level, seemingly unimportant portions of the procurement specifications often have tendency to change or be eliminated from the final version of specifications.

Once testing of these vehicles began on the at-grade portions of the alignment for this system, people living at the wayside began to complain about the noise. Prior to testing, it was not known what the specific problems were, but people indicated that the trains sounded very annoying, particularly at low speeds of less than 25 kph. Where the trains operated at higher speeds there were also complaints, but these were characterized more along the lines that the trains were simply noisy.

Since the transit agency believed that the trains were in compliance with the procurement specifications based on a series of field tests, it was not initially known why there were complaints, although transit staff did recognize that there was a strange noise from the propulsion system at speeds below 25 kph. A review of the procurement specifications regarding noise indicated the error regarding average noise level versus maximum noise level and that the basis for successfully passing the wayside noise test was, in fact, that L_{eq} was used for this evaluation rather than L_{max}.

Additional field tests were run comparing two of the new cars with two from the existing fleet. It was found that for typical low speed operations on the order of 15 kph, that the maximum noise levels from the new cars were 4 to 6 dBA greater, while for higher speed operations at 40 kph, the maximum noise levels from the new cars were 3 to 5 dBA greater. In addition, there was a strong pure-tone component from the propulsion system at speeds less than 25 kph. The pure tone noise was centered at a frequency of 1080 Hz and was associated with the A.C. propulsion system. These noise level increases plus the change in character of the train noise at low speeds was enough to generate community complaints.

Working with the vehicle manufacturer, the noise levels were eventually reduced. The propulsion system noise and associated pure-tone components were reduced with changes in the propulsion control software such that there was no longer such a strong peak at 1080 Hz. It was determined that the increase in noise levels at higher speeds was most pronounced on embedded track. The new vehicles had self-ventilated traction motors, while the existing vehicles had forced ventilated traction motors. This increase in noise level is consistent with what has been found at other systems, where vehicles with self-ventilated traction motors exhibit higher noise levels on embedded track due to the noise emitted from the ventilation element of the traction motor which is reflected off the hard pavement of the street. Additional efforts by the vehicle manufacturer regarding the ventilation system did result in some noise reduction of the wayside noise, such that the majority of community complaints regarding noise finally stopped.

Rough Track at Special Trackwork

In December 2008 Valley Metro Rail opened a new light rail system based in Phoenix, Arizona. The system features embedded track for most of its alignment, with special trackwork encompassing crossovers located at strategic points throughout the system. After initial startup, numerous community complaints were received regarding excessive noise and vibration particularly at locations near the crossovers. The system typically employs two single crossovers rather than using double crossovers. Each single crossover employs two turnouts to cross from one track to the other.

Trains traversing the special trackwork associated with turnouts and crossovers do typically generate higher levels of both vibration and noise due to the discontinuities of the track structure (usually highest when traversing the gap of the switch frog). Figure 4 shows one of the single crossovers.

Figure 4. Single Crossover of Embedded Track

Noise measurements following initial complaints indicated that using the recommended noise criteria of the FTA Guidance Manual using the hourly L_{eq} or long-term (24hour) L_{dn}, indicated that criteria compliance were achieved since the relatively short-duration increase in noise level was not significant when averaged out over a long time period.

Inspection of the rail in the area of the crossovers indicated very rough rail as a consequence of the manner in which the rail was installed. Although some effort had been made to smooth the rail, it was clearly very rough and contributed significantly to both the noise and vibration with each passing train. Figure 5 shows a portion of rough running rail at the top of the photograph.

Figure 5. Example of Rough Running Rail (at top)

Since the transit agency was still receiving complaints of both noise and vibration, vibration measurements were obtained with the belief that there could be feelable levels of groundborne vibration inside some of the adjacent buildings. However, based on the measurement results, it appears that those annoyed by what they perceived as vibration may actually have been more annoyed by the higher levels of short-duration airborne noise, which can also be perceived as vibration due to secondary vibration effects such as rattling of windows or objects within a room. So here is a situation where the recommended criteria of the FTA Guidance Manual is achieved for both noise and vibration, yet complaints of noise and vibration from train operations continued.

There are no FTA recommended noise or vibration criteria for restaurants. Unfortunately, a restaurant is located immediately adjacent to one of the turnouts of a crossover. The restaurant also has an outside seating area which is even closer to the tracks than the inside portion of the restaurant in the building itself. There are condominiums or apartments located above the restaurant. Although there were complaints from both the restaurant owner and residents above the restaurant, this is an unusual situation for enjoyment of the outside area of the restaurant is predicated on reasonable noise levels. Here the FTA recommended criteria only apply to the residential dwellings. Figure 6 shows a view of a train approaching the crossover with the restaurant to the left of the photograph. Figure 7 shows the outside seating area with the dwelling units above the restaurant.

Figure 6. Train approaching crossover with restaurant at left

Figure 7. Outside seating area of restaurant with dwellings above

Overall the change in character of the noise due to impacts and rough rail as the trains pass through the crossover appears to be the primary basis of annoyance and complaints such that grinding the rough rail should eliminate or reduce this annoyance. At present, the transit agency is in the process of doing just that.

Wheel Squeal at Curves

Wheel squeal is a phenomenon of rail transit that can be particularly irritating to wayside residential areas. It is a localized problem, usually occurring only at relatively short-radius curves, and is caused by wheel surfaces rubbing or sliding on the rails, specifically the stick-slip motion between the wheels and rails. Although there are features on the Valley Metro Rail vehicle specifically designed to eliminate wheel squeal, a group of residents in the Hayden Square Condominium Complex in the city of Tempe, Arizona made many complaints about the wheel squeal noise generated by trains travelling adjacent to their residential complex.

The Valley Metro light rail vehicle is made by Kinkisharyo and is a 27.5 m long articulated vehicle with a low floor area between the two end trucks. The two end trucks are powered, while the center truck is un-powered with no connecting axles between the wheels. The end trucks are two-axle trucks with wheels that are rigidly attached to the axles and the axles rigidly attached to the truck. When the truck traverses the curve, several factors can cause wheel squeal. One is the difference in the distance traveled by the inner and outer wheels. On a relatively sharp curve, the inner and outer wheels will attempt to roll at difference speeds with the resulting differential movement compensated by one or both of the wheels slipping on the rails, causing wheel squeal. Another cause of wheel squeal is the crabbing of the trucks as they traverse the curve. For a rigid truck where the axles are forced to remain parallel, they can never both lie on the radii of the curve. At least one of the wheel pairs must roll at an angle to the rails, which creates a slippage of the wheel running surface across the rail. There are some recent studies which discuss the mechanisms and types of wheel squeal in more detail, but for this paper these generic descriptions of the mechanism of wheel squeal should suffice.

There are four general approaches for controlling wheel squeal:

- Reduce the energy, created by the wheel sliding or rubbing on the rail, by lubricating the rail surface.
- Absorb the vibrational energy before it is radiated by using damped or resilient wheels.
- Block the sound energy before it reaches the receiver with the use of a sound barrier.
- Prevent stick-slip at the wheel/rail interface with articulated or steerable trucks.

The Kinkisharyo vehicle utilizes resilient wheels and has the REBS on-board centralized lubrication system for lubricating or applying a friction modifier to both the wheel flange (WFTL or Wheel Flange Turbo Lubrication) and top of rail (TOR). The lubrication control systems are governed by GPS (Global Positioning System) so that the appropriate lubrication can be applied at specific locations throughout the system on a vehicle by vehicle basis. In addition the vehicle has wheel skirts which extend over the trucks down to the base of the vehicle shell. It is clear that the resilient wheels and wheel skirts by themselves do not eliminate the wheel squeal. Along with minimizing wheel/rail wear, the REBS system is specifically designed to completely eliminate wheel squeal on short radius curves. The friction modifier called ALL_RAIL is a semi-fluid composed primarily of vegetable oils and is biodegradable and insoluble in water, so the material should adhere to the rail even during periods of rain. Based on experience at other transit agencies (primarily European) using the REBS system, appropriate adjustment of the system should eliminate wheel squeal under all conditions.

As indicated, the primary complaint regarding noise from Valley Metro Rail operations focused on the wheel squeal which emanates from the light rail vehicles as they traverse the curve on the west side of the Mill Avenue/Third Street Station. The westbound track has a radius of 145 m, while the eastbound track has a radius of 150 m. The two tracks are separated by 4.5 m through the curve. The civil speed limit for the curve is 32 kph. The eastbound track centreline is approximately 21 m from the nearest condominium unit. Figure 8 shows the curved tracks, with a large parking structure on the left of the photograph and the condominiums on the right side of the photograph.

Figure 8. Curve near Hayden Square Condominiums

Due to the complaints, a preliminary set of noise measurements was obtained in February 2009 which found that although many trains produced wheel squeal when traversing the curve, the noise levels measured over a 6-hour period and compared with a baseline L_{dn} indicated compliance with the FTA Guidance Manual recommended criterion for residential dwellings. However, this was not a complete 24-hour measurement and was considered preliminary, at best. One of the reasons that this study may have indicated compliance with the recommended criterion is that the area is on the flight path for Phoenix Sky Harbor Airport, so there are numerous jet flyovers which generate high levels of noise primarily during non-sleeping hours. There are also other noise sources from nearby street traffic.

Ironically an extremely detailed noise study undertaken by this author in November 2009 at three measurement locations over several days indicated virtually no wheel squeal noise when the trains traversed the curve. The residents then believed that the transit agency had done something special during these measurements to eliminate the squeal so that the problem could be ignored. On the contrary, there were very few people at the agency that even knew that such a study was being undertaken, as much of the coordination had taken place through personnel at the city of Tempe.

Although it was unknown why wheel squeal was not present during the November 2009 study, it was understood by most involved, that the REBS centralized lubrication system was fully functional during that period of time. However, shortly after these measurements it was clear that the wheel squeal had not been consistently eliminated. For that reason, a number of alternative mitigation measures were developed including improving the noise insulation of the existing doors and windows of the condominiums, or constructing a sound barrier wall between the rail alignment and the condominium complex.

Further investigation with the company that supplied the REBS centralized lubrication system to Valley Metro Rail indicated that the system had not been setup properly since the startup of the system. Although only small amounts of friction modifier are necessary for the system to work properly, the system had not been activated on all of the cars, the TOR system had not been activated on any cars, and the GPS coordinates were incorrect. Apparently, with the efforts to get the system ready for revenue service by the date promised to the public and subsequent efforts to maintain basic operations when a new group of vehicle service personnel, the REBS system was never optimized. Once the system was optimized for this location as well as others throughout the system, the wheel squeal was controlled and the number of complaints has decreased significantly. Unfortunately, this noise issue has raised the residents concerns about other noises associated with the operation of the rail system, including the electronic bells on the train, the train horn, public address announcements emanating from the station across from the condominium complex and the crossing gate bells located at street crossings both east and west of the complex.

In summary, if the REBS centralized lubrication system had been setup properly from the start of revenue operations, the transit agency could have saved the money for the noise studies and avoided the bad feelings that the condominium complex residents have regarding the transit agency, the city of Tempe and the operation of the trains.

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