SAE International

Vehicle Pass-by Noise Estimations for Component-Level Design

2011-01-1608
Published
05/17/2011

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doi:10.4271/2011-01-1608

ABSTRACT

Design parameters for automotive components can be highly affected by the requirements imposed for vehicle pass-by compliance. The key systems affecting pass-by performance generally include the engine, tires, intake system, and exhaust system. The development of these systems is often reliant on the availability of prototype hardware for physical testing on a pass-by course, which can lead to long and potentially costly development cycles. These development cycles can benefit significantly from the ability to utilize analytical data to guide development of component-level design parameters related to pass-by noise.

To achieve this goal, test and analysis methods were developed to estimate the vehicle-level pass-by performance from component level data, both from physical and/or analytical sources. The result allows for the estimation of the overall vehicle-level pass-by noise along with the contributions to the total and dominant frequency content from each of the key noise sources. This information can be utilized in two distinctly different ways. First, the pass-by noise levels can be estimated for new component-level design alternatives, from either physical testing and/or analytical predictions. Secondly, a target pass-by noise level can be specified and the required acoustic performance for the dominant noise sources can be calculated.

Utilizing component-level data to estimate vehicle pass-by performance provides the ability to evaluate multiple design alternatives in a time and cost-effective manner, as well as balance potential countermeasures and design alternatives across multiple noise sources. Dependency on physical prototype hardware can be reduced, allowing for estimation of pass-by noise levels with reduced reliance on vehicle-level testing.

INTRODUCTION

One of the many regulations vehicle manufacturers are required to adhere to is vehicle pass-by noise. This purpose of this regulation is to minimize the emitted sound levels of vehicles under typical urban traffic conditions. This regulation has a direct impact on vehicle manufacturers and the methods that are used to design the key components that affect vehicle pass-by noise. In addition to designing components which improve the user experience inside the vehicle, the design of these components must also allow for compliance with pass-by noise regulations.

Vehicle pass-by noise is typically measured at an outdoor facility composed of a straight section of pavement and two measurement microphones. The vehicle accelerates between the set of microphones and the maximum sound pressure level at the two microphones is recorded. For regulatory purposes, the only relevant information is the overall A-weighted sound pressure level. For vehicle manufacturers the overall level is certainly of importance, but of significantly more use is the knowledge of which systems and components on the vehicle are mostly responsible for these sound levels. In addition, it is critical to understand which frequency ranges are dominating the overall noise levels to aid in any necessary troubleshooting activities to reduce the overall pass-by noise levels of the vehicle.

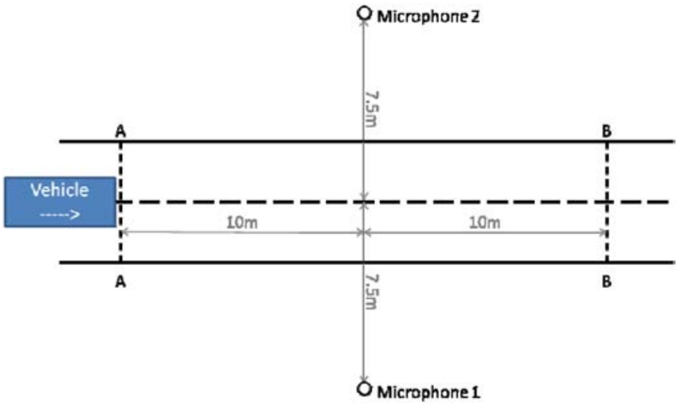

Figure 1. Typical Pass-by Noise Course

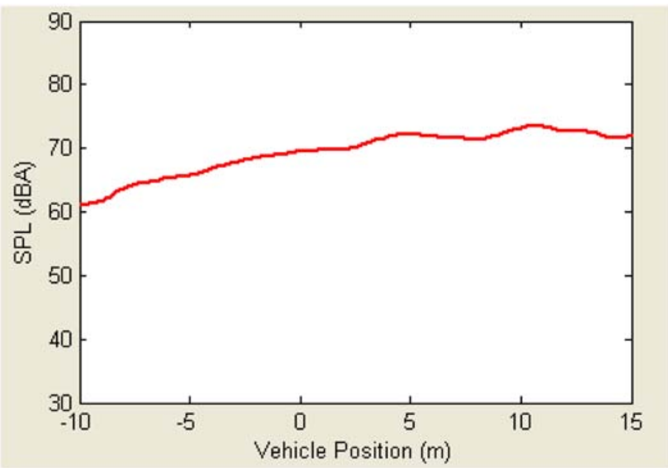

Figure 2. Sample Pass-by Noise Measurement

Unfortunately the knowledge of which systems are responsible for the sound levels is not readily available solely from physical vehicle pass-by noise measurements. To gather this information, additional efforts are necessary to modify the vehicle to "remove" the contributions from individual sources to determine how much the individual source contributes to the overall noise levels. This process must be repeated for each of the key noise generating systems to determine the relative contributions from each system. Only then is the vehicle manufacturer armed with enough information to effectively target engineering resources toward reducing the noise levels of the systems/components with the highest contributions.

For most gasoline powered vehicles, the noise sources that have the highest contributions to the overall sound levels are typically the exhaust system, intake system, engine noise, and tires. To understand the contributions of each of these sources to the total noise levels, physical tests are generally conducted to either isolate or mask each of these systems. For tire noise, the vehicle is generally run through the pass-by course with the engine turned off, therefore leaving the tires as the only noise generating system. To isolate the intake or exhaust noise, each system is often ported into a large externally mounted muffler system designed to remove a large portion of the noise levels. This generally provides a large reduction in the noise levels from each of these systems, however does not completely remove them. The radiated engine noise contributions are often estimated by subtracting the contributions from each of the other systems (tires, intake, and exhaust) from the total, with the remaining levels assumed to be due to the engine radiated noise.

While this physical testing approach to estimating contributions can be beneficial, it also requires a significant time and resource investment due to the need for external muffler systems. Additionally, this method does not easily lend itself to a detailed understanding of how the relative contributions between the key systems change as the vehicle travels through the pass-by course.

Of more use to a vehicle manufacturer is the ability to estimate the contributions from each of the key noise sources without the need for additional hardware and test runs to isolate or mask each of the systems that also provides the contributions relative to the vehicle position on the pass-by course. This can allow for efficiently designing systems and components for improved pass-by performance.

PASS-BY NOISE ESTIMATIONS

Vehicle pass-by noise, in its simplest form, can be viewed as a source-path-receiver model. The vehicle is composed of multiple acoustic sources which all radiate sound. The sound interacts with the geometric features of the vehicle and with other nearby noise sources, and travels from the vehicle into free-space toward each of the pass-by microphones. The sound from each of the key noise sources has its own unique path from the source to the receiver, in this case the pass-by microphones. To estimate the pass-by noise levels, each acoustic source and each path (transfer function) needs to be characterized. At any given vehicle position within the course, the sound at the pass-by microphones is the summation of the products of the radiated sound of each of the noise sources and their respective transfer functions, all of which are a function of frequency.

$$\text{Pass-by Estimation} = \sum [\text{Source}(f)_i \times \text{Path}(f)_i] \;\; \text{for } i = \text{all acoustic sources}$$

One benefit of utilizing these methods to estimate pass-by noise levels is the availability of not only the total noise levels, but also the contributions from each of the noise sources included in the calculations. This information can be available for all course position at which calculations are conducted, so it is possible to identify the different areas of the course in which the pass-by noise levels are dominated by different sources.

Figure 3 highlights sample pass-by noise estimations, including both the overall sound levels and the contributions from several of the key noise sources. This working example, which will be utilized to aid the discussion throughout this paper, was generated from measured sound pressure levels at each of the key noise sources on a test vehicle during a simulated pass-by run on a chassis dynamometer, along with objectively measured transfer functions using a volume velocity source.

In this example it can be noted that the vehicle intake system is the dominant noise source throughout the middle of the pass-by course, while the exhaust system is dominant toward the exit of the course. This information can be used to strategically allocate engineering resources toward the appropriate systems of the vehicle to reduce the pass-by noise of the vehicle. In this example the peak pass-by noise level exists at the end of the course (+10m), which is largely due to the exhaust system. To reduce this peak value, design efforts should focus on the exhaust system.

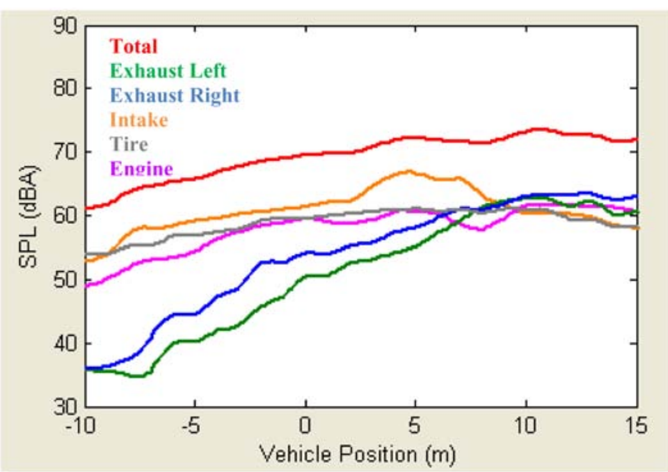

Figure 3. Sample Pass-by Noise Levels with Contributions

If improvements were made to the exhaust system resulting in a reduction of the pass-by noise levels at the end of the course (+10m), the resulting pass-by levels would likely remain unchanged at the middle of the course (+5m) which is dominated by intake system noise. Without the availability of the individual contributions from all the sources, one would not know which system was dominating the overall noise levels, and thus which system to continue development to reduce pass-by noise levels.

Another benefit for estimating the pass-by noise levels as the sum of the contributions is the availability of frequency domain data. If the dominant noise source has been identified, it is also of importance to understand the frequencies that are dominating the overall sound levels for this specific noise source. Figure 4 highlights frequency domain data at a particular course position for the sample pass-by noise estimations. From the frequency domain data it is possible to identify the particular frequency or frequencies that would need to be modified to reduce the contributions from any particular source, and thus reduce the overall pass-by noise levels. In this example, the dominant frequencies for the exhaust contributions (at this particular course position) include 190, 380, and 570 Hz., all of which have similar amplitude. To reduce the exhaust contributions at this course position, modifications would likely need to be made to the system at all three frequency ranges to achieve an appreciable change to the overall pass-by noise levels.

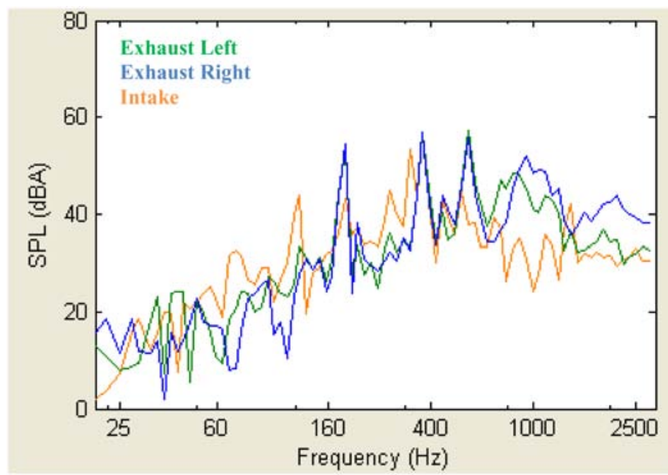

Figure 4. Sample Frequency Spectra

To fully utilize the estimations of pass-by noise, we would want the ability to use the frequency domain pass-by contributions to help support the engineering design processes. Of most benefit is to understand how much of a reduction to the maximum pass-by noise levels could be achieved for a specific design change to one the vehicle systems, for example a change to the attenuation characteristics of the exhaust system at only one frequency. Alternatively the information could be used to determine the required change to an individual system or multiple systems to achieve a target value for peak pass-by noise, allowing for system and/or component level target setting that can be communicated to the engineering team and supply base.

COMPONENT DESIGN FOR PASS-BY NOISE

One strategy to design components for pass-by noise compliance is to utilize physical testing. The results of physical testing can be used in combination with prior knowledge, surrogate vehicle data, and engineering judgments to define component level acoustic targets and requirements. One benefit for utilizing this strategy is that it provides an absolute number for pass-by performance for the vehicle evaluated. Drawbacks for utilizing a physical testing strategy include the necessity for prototype systems and components along with the need for prototype vehicles, all of which can be difficult to obtain particularly early in the vehicle development process. Additionally the physical testing approach requires accessibility of a pass-by course along with the appropriate weather conditions to facilitate the testing. To begin to assemble estimates of the contributions from specific vehicle systems, large external muffler systems are generally required during the testing, which significantly increases the necessary test time and support from test engineers and support staff, and can affect the overall performance of the vehicle.

An alternative strategy to design components is to utilize predictive tools to assess pass-by noise compliance in cooperation with a limited set of initial physical tests. A benefit for utilizing this strategy is that it provides the ability to estimate pass-by performance for all future system and component-level design alternatives with limited need for physical prototypes. Once the initial physical testing has been conducted to provide a characterization of the key noises sources and paths, additional physical testing is not required to evaluate design changes during the engineering design process, but rather just for final validation of performance. Additionally this method is not dependent on the availability of additional prototype vehicles, prototype systems and components, or suitable weather conditions for outdoor testing. Component level noise performance estimates from analytical models, such as 1D simulation models, can be fed into the vehicle level pass-by noise estimates to gauge vehicle level performance relative to targets. This method also provides detailed information relative to the contributions from specific noise sources throughout the pass-by course, information that is not available utilizing only a physical testing approach. A drawback for this method is that the pass-by noise levels are only estimates, and physical testing of the 'optimum' solution is required for confirmation.

The predictive approach for pass-by noise design also allows for the understanding of the critical areas of the component design that impact pass-by noise levels. The required design solutions necessary to achieve the target pass-by noise criteria for any given component or system may be in direct conflict with design solutions necessary to achieve other vehicle level attribute targets such as interior noise requirements. Evaluating design options analytically can allow for development of a balanced solution to achieve both requirements.

Another key benefit to the predictive approach is that is can help to eliminate waste in engineering design efforts. Full knowledge of the key systems, components, and frequency ranges impacting the pass-by noise performance allow for focused efforts in only the areas which are important for pass-by noise. If pass-by noise can be reduced by affecting more than one system or component, multiple systems design alternatives can be evaluated to identify the most efficient solution.

USE OF PASS-BY NOISE ESTIMATIONS FOR COMPONENT DESIGN

With the availability of contributions from each of the key acoustic sources to the overall sound pressure levels at the pass-by microphones across the entire pass-by course, the information can be used in two distinctively different ways to support design and development of the systems and components.

Pass-by levels can be estimated for new component level design alternatives, from either physical testing and/or analytical predictions. Engineering time and effort can be utilized only for the design options that provide the required performance for pass-by noise.

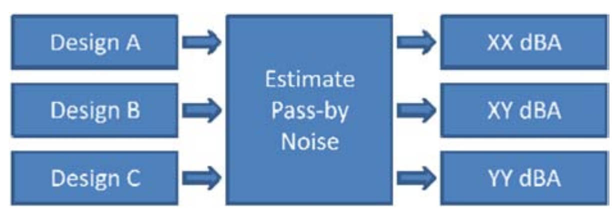

Figure 5. Estimation of Pass-by Performance from Design Alternatives

Alternatively, the target pass-by noise level can be specified and the required acoustic performance to achieve this target for the dominant noise sources can be calculated. This can provide design targets/alternatives for individual or multiple systems.

Figure 6. Component Design Criteria to Achieve Pass-by Target

ESTIMATE PASS-BY PERFORMANCE FOR DESIGN ALTERNATIVES

When designing components that have an impact on the pass-by noise performance of the vehicle, it would be beneficial to be able to evaluate various design alternatives analytically to understand the expected pass-by noise performance for each. This information can help to include or exclude various design solutions for being pursued further by the engineering design teams.

The underlying assumption for the estimation of vehicle pass-by noise levels is that of a source-path-receiver model. For design modifications/alternatives made to any individual component, the path term remains constant, as does the individual contributions at the pass-by microphone from all of the other noise sources. The only piece that changes is the nearfield acoustic radiation of the noise source under investigation. This will generally hold true for small to moderate changes to a single source with the assumption that all of the noise sources are incoherent. Larger changes to a single component may however result in changes to other systems. One example is coupling of the exhaust and intake systems. For large changes which have a significant impact on backpressure, changes to the exhaust system may be accompanied by changes to the intake system.

If the desire is to understand the expected pass-by noise performance of Alternative A relative to the performance of a baseline design, then it is possible to characterize the difference in acoustic radiation between the two designs at the vehicle level or at the component level. As discussed earlier, evaluating the differences at the vehicle level generally tends to be costly and inefficient. By evaluated the differences in performance at the component level, analytical models and/or component level evaluations can be conducted, and the results can be input into the pass-by noise estimations to determine the expected impact to the overall sound pressure levels at the pass-by microphones.

Utilizing the pass-by noise estimates noted in Figure 3, the peak pass-by noise level exists toward the end of the course, near +10m. By evaluating the available contributions of the key noise sources we can identify the exhaust system as a dominant contributor to the overall pass-by noise. Interrogation of the exhaust contributions in the frequency domain, Figure 4, identifies three main frequencies: 190, 380, and 570 Hz. As discussed earlier, these contributions are the product of the radiated noise nearfield to the exhaust (source) and the transfer function between the exhaust system and the pass-by microphone (path). To estimate the pass-by noise performance for exhaust design alternatives, the exhaust source data can be modified and combined with the path term to calculate a predicted contribution at the pass-by microphone. The exhaust contribution can then be summed with the contributions from the other noise sources to predict the total pass-by noise performance.

To accomplish this, the exhaust source data needs to be modified through a series of digital filters to mimic the expected differences between the baseline exhaust system and any design alternatives. As an example, an exhaust alternative can be evaluated that is expected to have an additional 10dB of attenuation (at the component level) centered around 380 Hz. The results, highlighted in Figure 7 and Figure 8, shows the predicted impact of the design change to the frequency domain exhaust contributions, total exhaust contributions, and the overall pass-by noise levels of the vehicle. In the frequency domain, the estimated change for the 'new' exhaust system is 10dB lower that the baseline system in the frequency range modified. The effect of this change on the overall exhaust contributions, however, is much smaller with a reduction of only 1.1dB around the +10m course position. This change to the exhaust contribution reduced the total pass-by noise peak level by only 0.5dB.

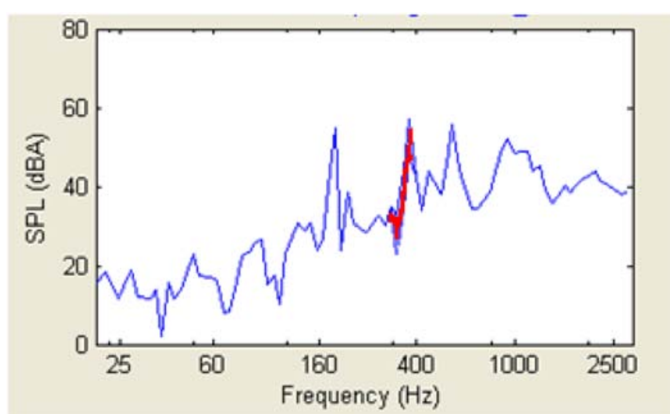

Figure 7. Design Alternative A - Exhaust Frequency Domain

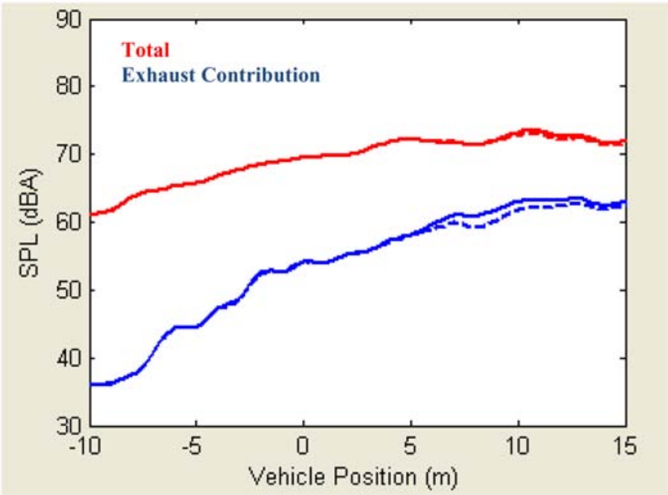

Figure 8. Design Alternative A - Total & Exhaust Contributions

By performing additional calculations, the impact of any proposed design modifications can be evaluated. We can evaluated the expected pass-by noise performance for an exhaust system that has been modified at each of the three key frequencies identified (190, 380, and 570 Hz.) in the working example. The predicted results from this configuration are noted in Figure 9. In this configuration the overall exhaust contribution estimates were reduced by 3.0dB, while the total pass-by noise peak level was reduced by 1.3dB.

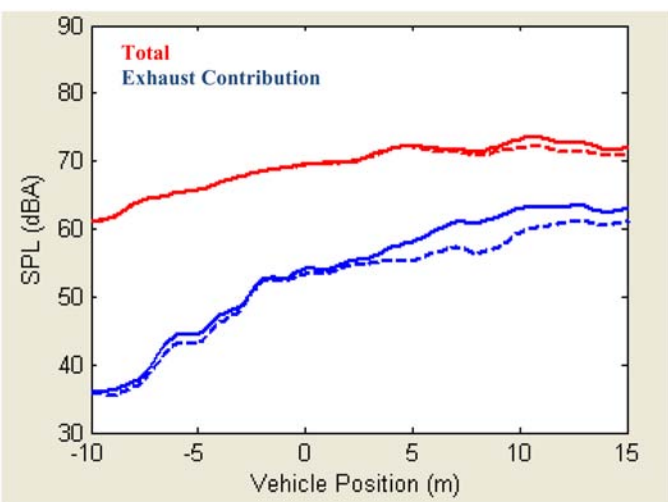

Figure 9. Design Alternative B - Total & Exhaust Contributions

This process can be repeated for any number of design alternatives for a single noise source, as well as for a combination of several noise sources. This method provides an approach to evaluating the expected pass-by noise performance for different component designs which could come from any number of places, including recommendations from the supply base, analytical models, component-level hardware evaluations, or engineering judgments.

DETERMINE COMPONENT DESIGN CRITERIA TO ACHIEVE PASS-BY TARGET

Although the trial-and-error based approach described above has its benefits, specifically for evaluating potential design solutions, it is also of use to utilize a predictive approach to estimate the component-level requirements need to achieve a target pass-by noise level. Using the same source-path-receiver logic as described previously, a target pass-by noise level can be specified and the required performance of any key noise source can be calculated to achieve this target. This information is valuable because it provide guidance for the engineering design teams for the required acoustic performance of a component, to which functional prototype designs can be developed. This allows for the iterative process of assessing pass-by noise performance to be conducted analytically without the need for prototype hardware. Only when design iterations achieve the required performance indicated from the pass-by noise estimations will actual hardware become necessary.

The pass-by noise estimated noted in Figure 3 can again be used as a working example, now to highlight the development of component-level targets to achieve a specified pass-by noise target. In this example, the peak pass-by noise level is 73.4 dBA near +10m. If the overall pass-by target is assumed to be 71 dBA, then the goal is to determine how the key noise sources from the vehicle need to be re-designed to achieve this target. This could be accomplished through modification of only a single noise source, or could require modification of multiple noise sources.

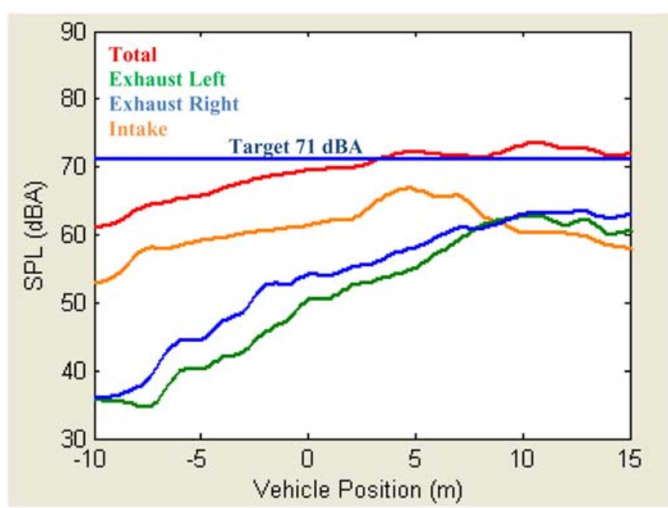

Figure 10. Sample Pass-by Noise Level Target

Utilizing the available contributions from each of the key noise sources, we can determine the change that would be required to the exhaust system in attempt to achieve the 71 dBA target. This calculation can utilize a 'goal-seek' type of algorithm to iteratively evaluate the overall pass-by noise and exhaust system contributions, determine the highest frequency domain peaks in the spectra, make modifications to the exhaust source noise, and re-combine these 'new' contributions with all of the other noise sources to estimate the overall effects on the pass-by performance. This process can be repeated to determine the minimal changes that would be required to the exhaust system to achieve the specified pass-by target.

Figure 11, Figure 12, and Figure 13 show the results of one such analysis. In this case it was determine that to achieve a pass-by noise level of 71 dBA the exhaust system would have to be modified to have an additional 15dB of attenuation at three discrete frequency ranges. These attenuation targets provide feedback to design engineers relative to how the exhaust system evaluated would have to be modified to achieve the pass-by target specified. Based on the available design envelope for each particular component and application, these changes may or may not be feasible with actual hardware. Thor these cases, modifications would have to be made to multiple noise sources to reduce the pass-by levels to the specified target. To aid this, the algorithms developed for this application allow the user to input realistic limits to the attenuation levels to avoid situations in which the algorithms would provide unachievable recommendations.

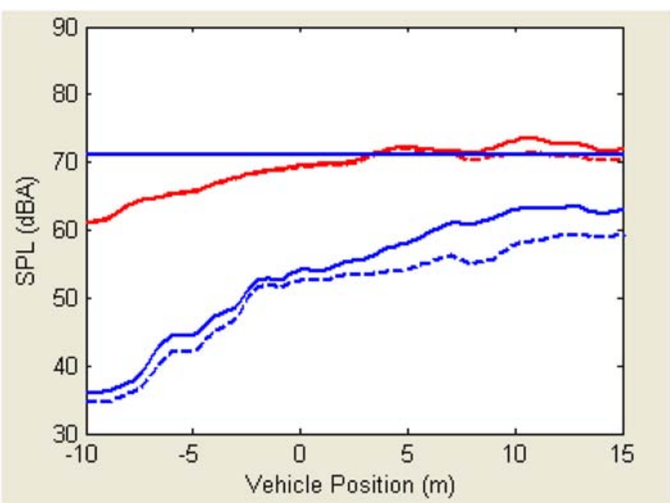

Figure 11. Modified Exhaust Contributions

Even in this case, with a rather substantial change to the exhaust system, the pass-by target is only achieved at the end of the course. Through the middle of the pass-by course, around +5m, the proposed modifications to the exhaust system had little effect on the overall pass-by noise and the target level of 71 dBA was not achieved. At this position of the course the overall pass-by noise is dominated by the intake system, so modifications to the exhaust system have little effect in this area.

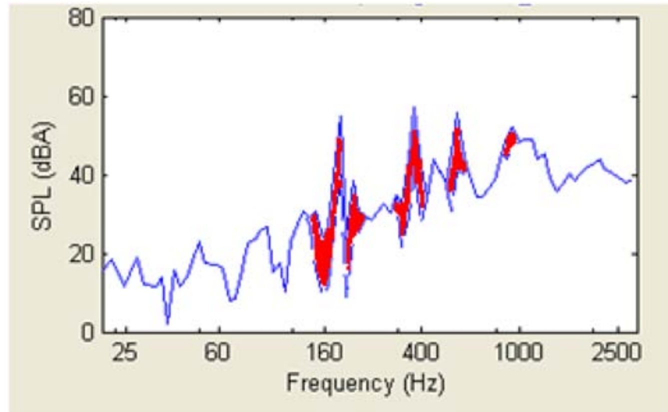

Figure 12. Modified Exhaust Frequency Spectra

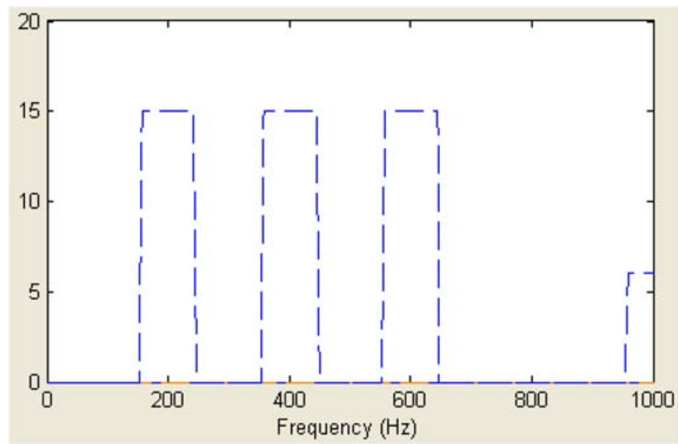

Figure 13. Modified Exhaust Profile

From this it can be concluded that the specified pass-by target cannot be achieved through modification of only the exhaust system. Just as easily we can evaluate if the target can be achieved through modification of only the intake system. The results from this analysis are noted in Figure 14. As expected, modifications to the intake system have an impact on the overall pass-by noise through the middle of the course, while the levels toward the end of the course are dominated by exhaust noise and therefore remain relatively unchanged.

We can now utilize the goal-seek analysis to understand the opportunities to achieve the pass-by noise target through combined modifications to both the intake and exhaust systems. This analysis provides an estimate of the minimal

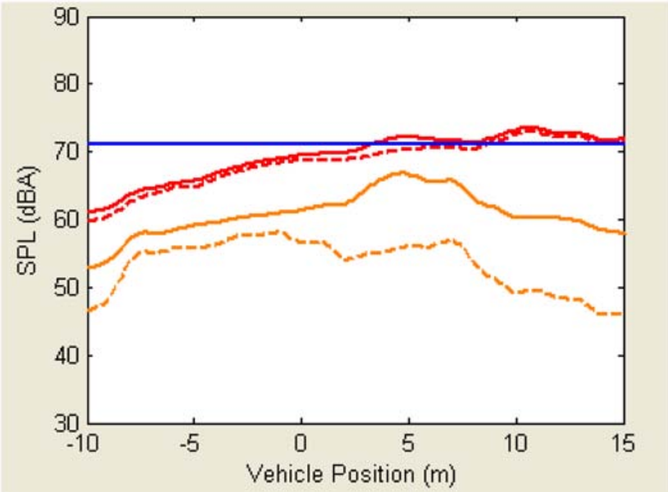

Figure 14. Modified Intake Contributions

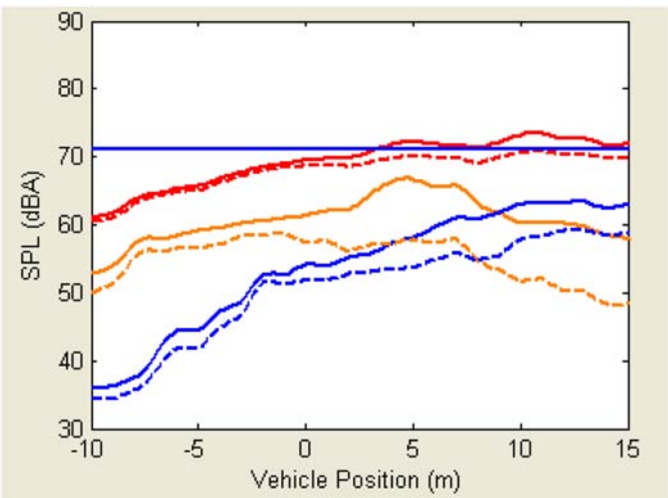

Figure 15. Modified Intake & Exhaust Contributions

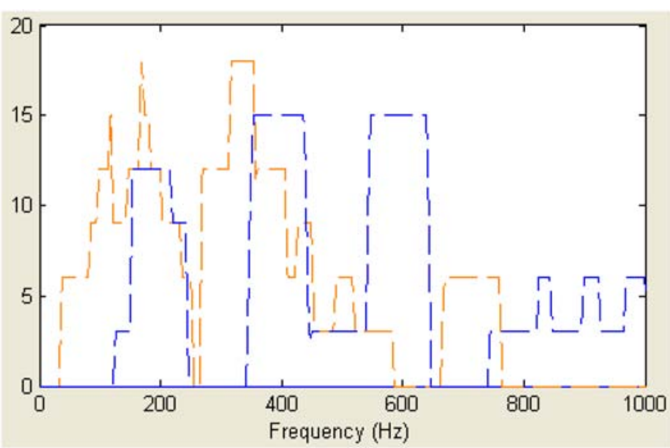

Figure 16. Modified Intake & Exhaust Profiles

changes that would be necessary to multiple systems to achieve a specified target. For this analysis a goal-seek algorithm can iteratively evaluate the overall pass-by noise along with individual contributions, determine the highest frequency domain peaks within the spectra, simulate modifications to the appropriate source noises, and re-combines the 'new' contributions with the remaining noise sources to estimate the overall effects on the pass-by performance. The results of this analysis are noted in Figure 15 and Figure 16.

SUMMARY/CONCLUSIONS

Through the use of predictive tools it is possible to significantly improve the efficiency of component level design efforts, as well as reduce the necessary impacts on time and costs required for physical testing based approaches. Development and utilization of predictive models can allow for evaluation of multiple design alternatives in a cost-effective manner without the reliance on vehicle-level testing.

This approach is particularly effective for development of vehicle pass-by noise performance in which multiple noise sources are present. For pass-by noise, a predictive approach can be utilized in two distinctively different ways. The pass-by levels can either be estimated for possible design alternatives, or the desired pass-by noise targets can be used to develop component-level design specifications. In either case a basic source-path-receiver model is used to characterize the acoustic radiation from each of the key noise sources on a vehicle along with their respective paths to the pass-by microphones. The result allows for the estimation of the overall vehicle-level pass-by noise along with the contributions to the total and dominant frequency content from each of the key noise sources.

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The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

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