Vibration and Noise Attenuation Methods

Main Attenuation Strategies

- Reduce the Input Forces from the Source
- Provide Isolation
- Mode Management
- Nodal Point Mounting
- Dynamic Absorbers

NVH Workshop Topic Outline

- Introduction
- Ride Balance in the Ride Range
- NVH Load Conditions
- Low Frequency Basics
- ***Live Noise Attenuation Demo***
- Mid Frequency Basics
- Utilization of Simulation Models
- Closing Remarks

Greg Goetchius

NVH Workshop Topic Outline

- Introduction
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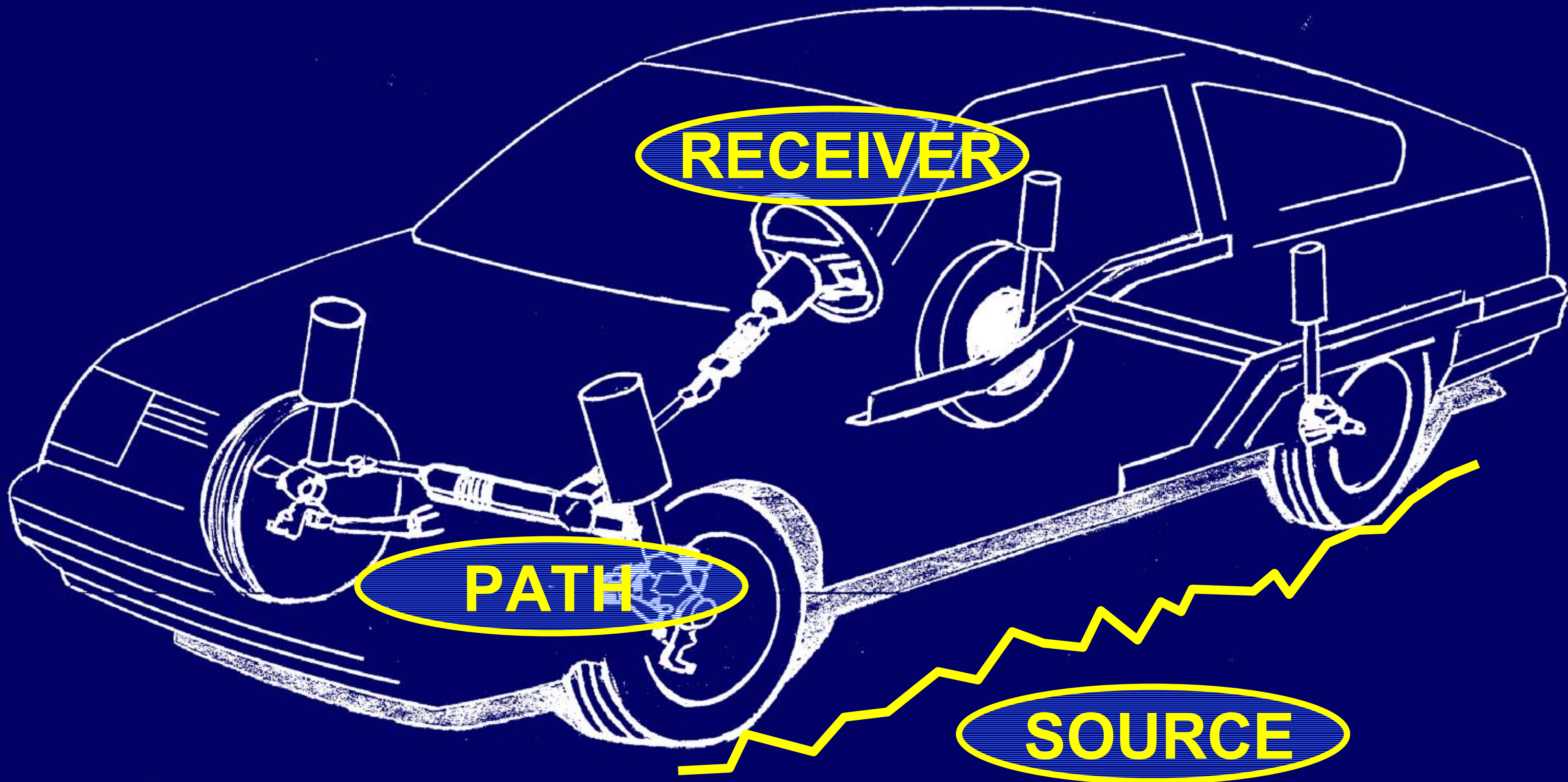
- *Live Noise Attenuation Demo*
- **Mid Frequency Basics**
- Utilization of Simulation Models
- Closing Remarks

Sachin Gogate

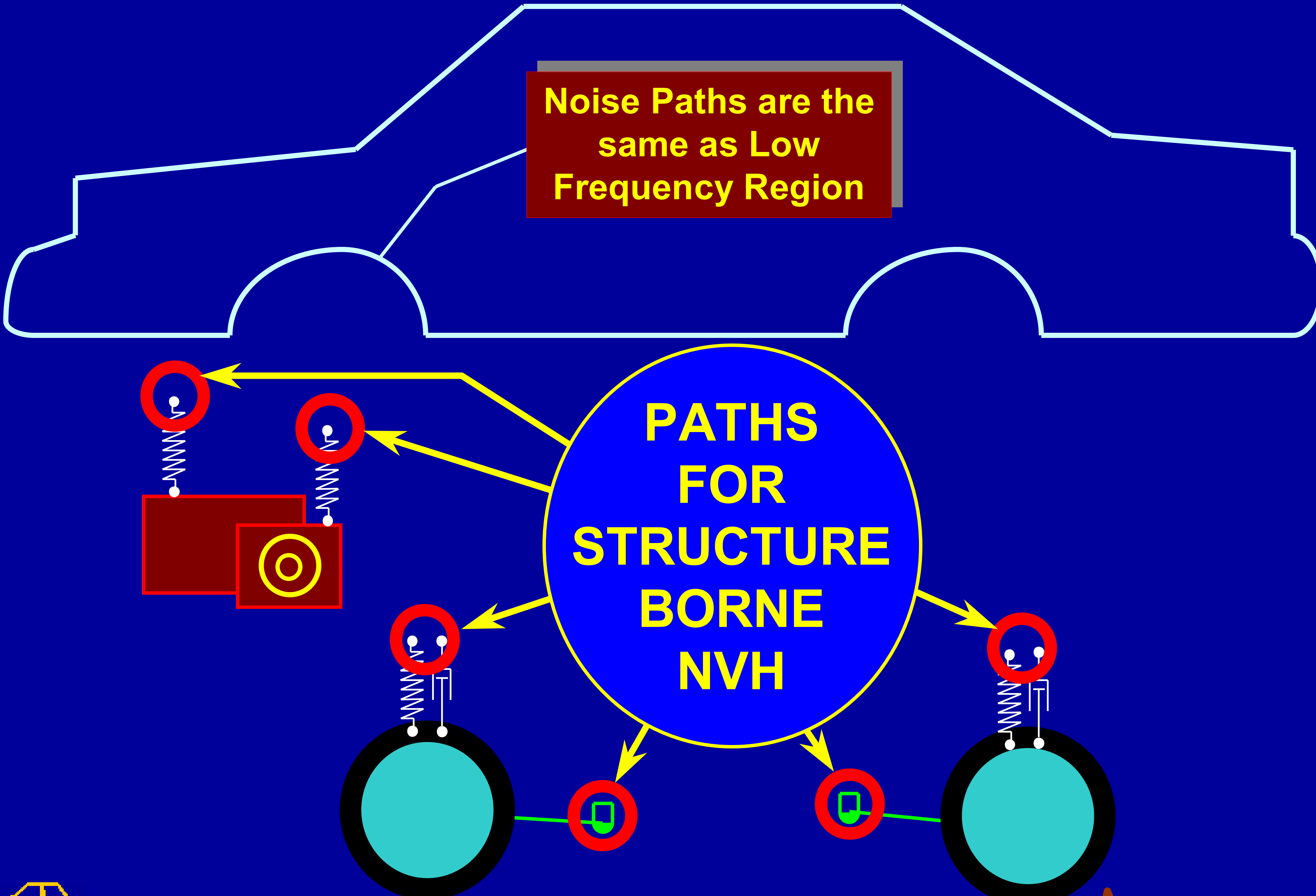
Mid Frequency NVH Fundamentals



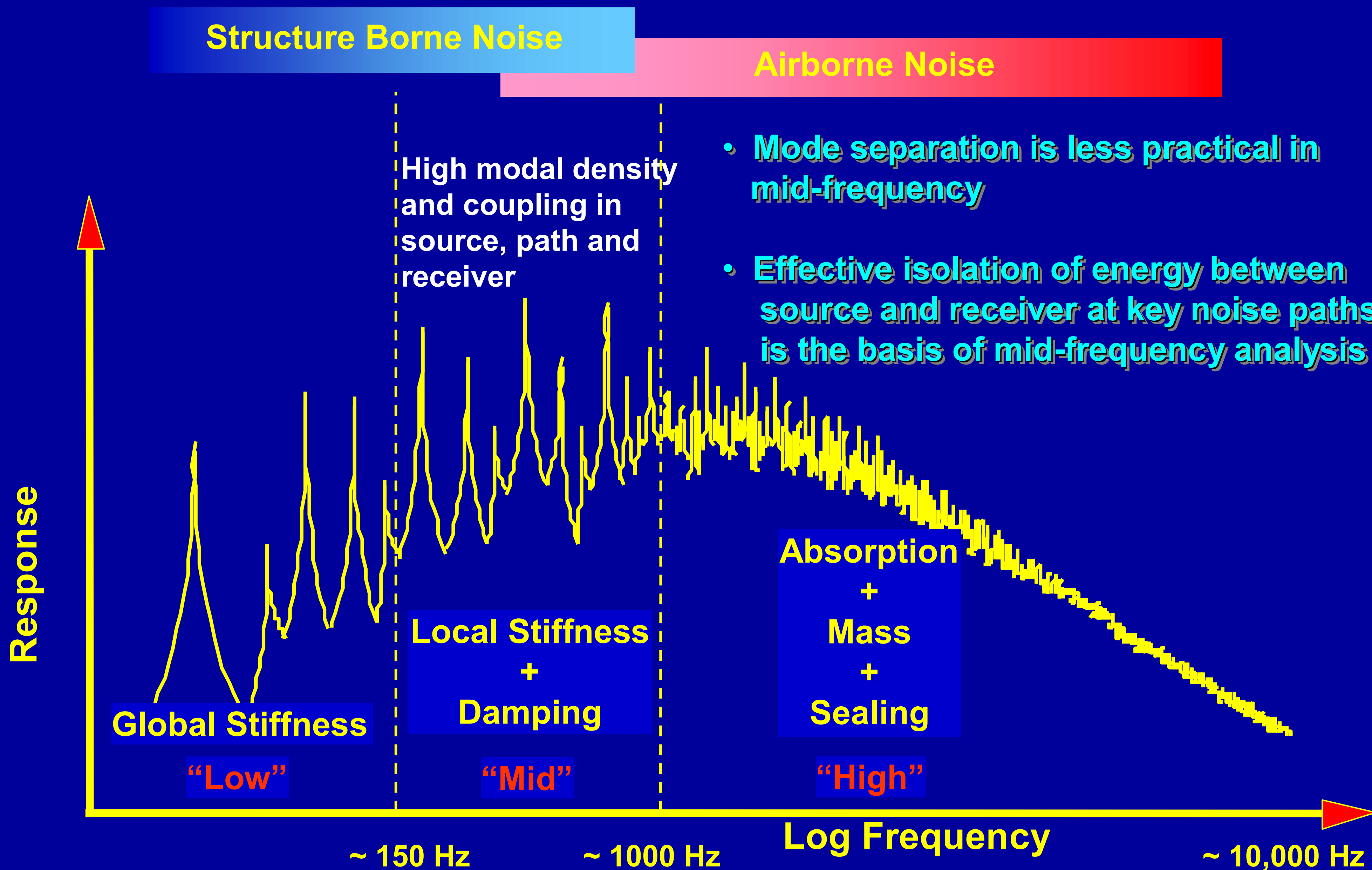
This looks familiar!

Frequency Range of Interest has changed to 150 Hz to 500 Hz

Typical NVH Pathways to the Passenger



Mid-Frequency Analysis Character



- Mode separation is less practical in mid-frequency
- Effective isolation of energy between source and receiver at key noise paths is the basis of mid-frequency analysis

Mid-Frequency Analysis Character

- Important characteristics of mid frequency analysis

Effective Isolation

&

Identifying Key Noise Paths

Mobility

- Mobility is the ratio of velocity response at the excitation point on structure where point force is applied

$$\text{Mobility} = \frac{\text{Velocity}}{\text{Force}}$$

- Mobility, also referred as Admittance, characterizes Dynamic Stiffness of the structure at load application point

$$\text{Mobility} = \frac{\text{Frequency * Displacement}}{\text{Force}}$$

$$= \frac{\text{Frequency}}{\text{Dynamic Stiffness}}$$

Mid-Frequency Analysis Character

- Important characteristics of mid frequency analysis

Effective Isolation

&

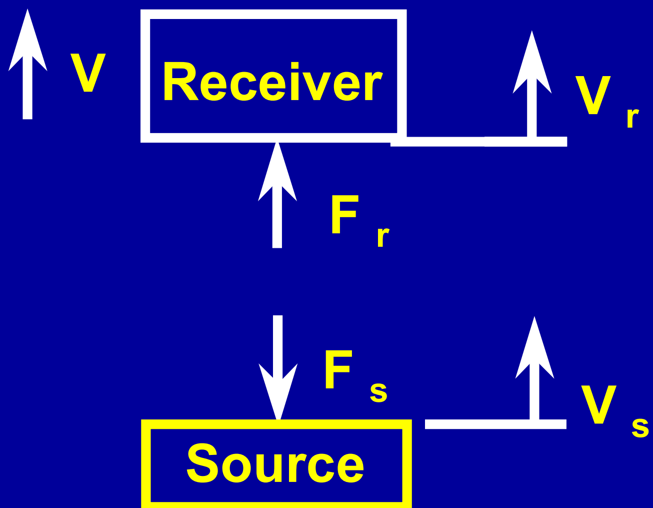
Identifying Key Noise Paths

Isolation

• The isolation effectiveness can be quantified by a theoretical model based on analysis of mobilities of receiver, isolator and source

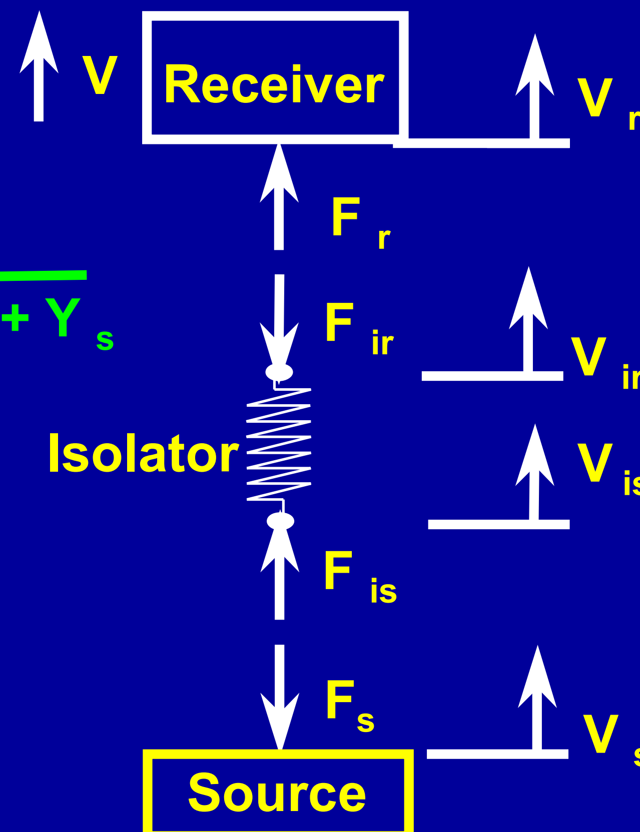
• Transmissibility ratio is used to objectively define measure of isolation

$$TR = \frac{\text{Force on source without isolator}}{\text{Force on source with isolator}}$$



$$F_s = \frac{V}{Y_r + Y_s}$$

$$F_s = \frac{V}{Y_i + Y_r + Y_s}$$



Isolation

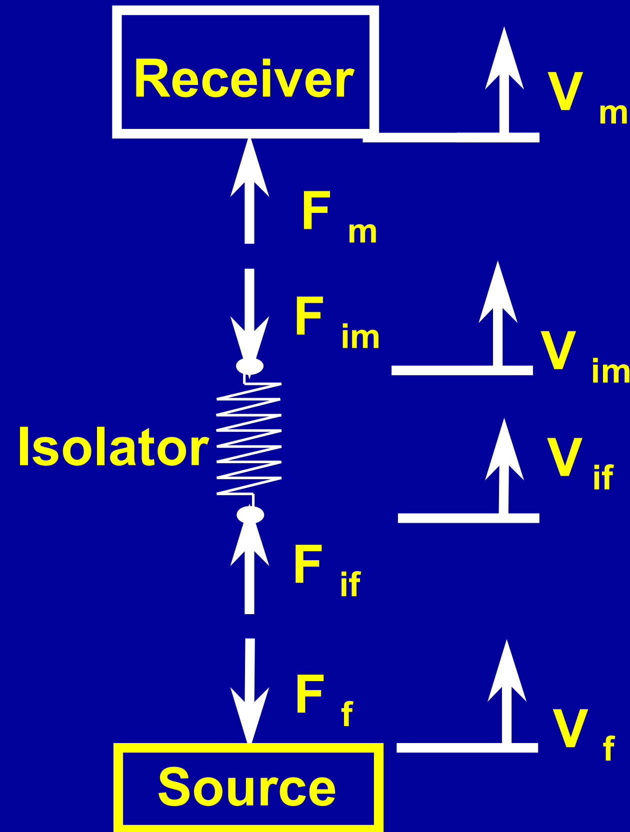
$$TR = \frac{\text{Force on source without any isolator}}{\text{Force on source with any isolator}}$$

$$TR = \left| (Y_r + Y_s) / (Y_i + Y_r + Y_s) \right|$$

Y_r : Receiver mobility

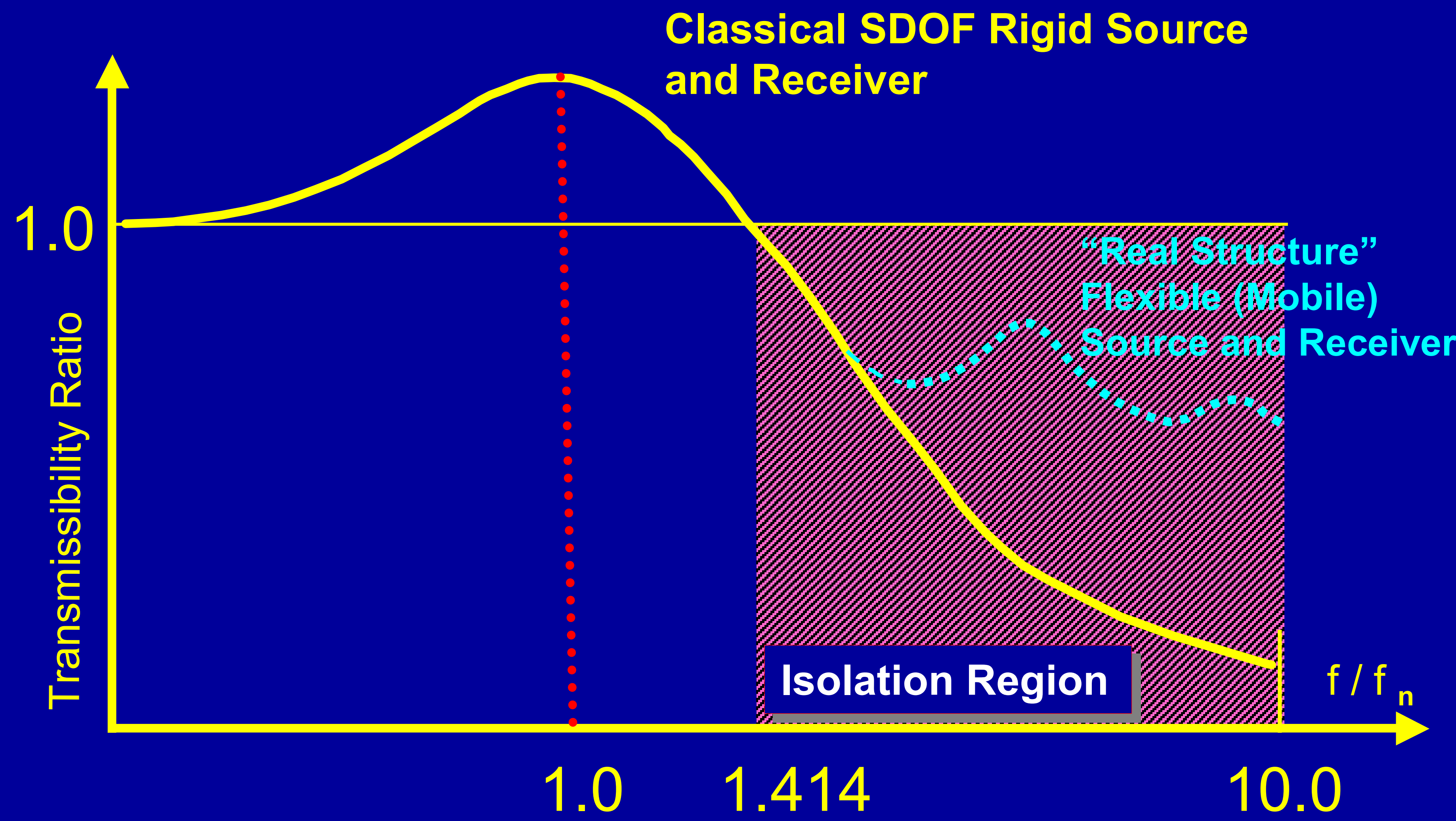
Y_i : Isolator mobility

Y_s : Source mobility



• *For Low Transmissibility the isolator mobility must exceed the sum of the Source and Receiver Mobilities.*

Isolation Effectiveness



Effectiveness deviates from the classical development as resonances occur in the receiver structure and in the foundation of the source.

Mid-Frequency Analysis Character

- **Important characteristics of mid frequency analysis**

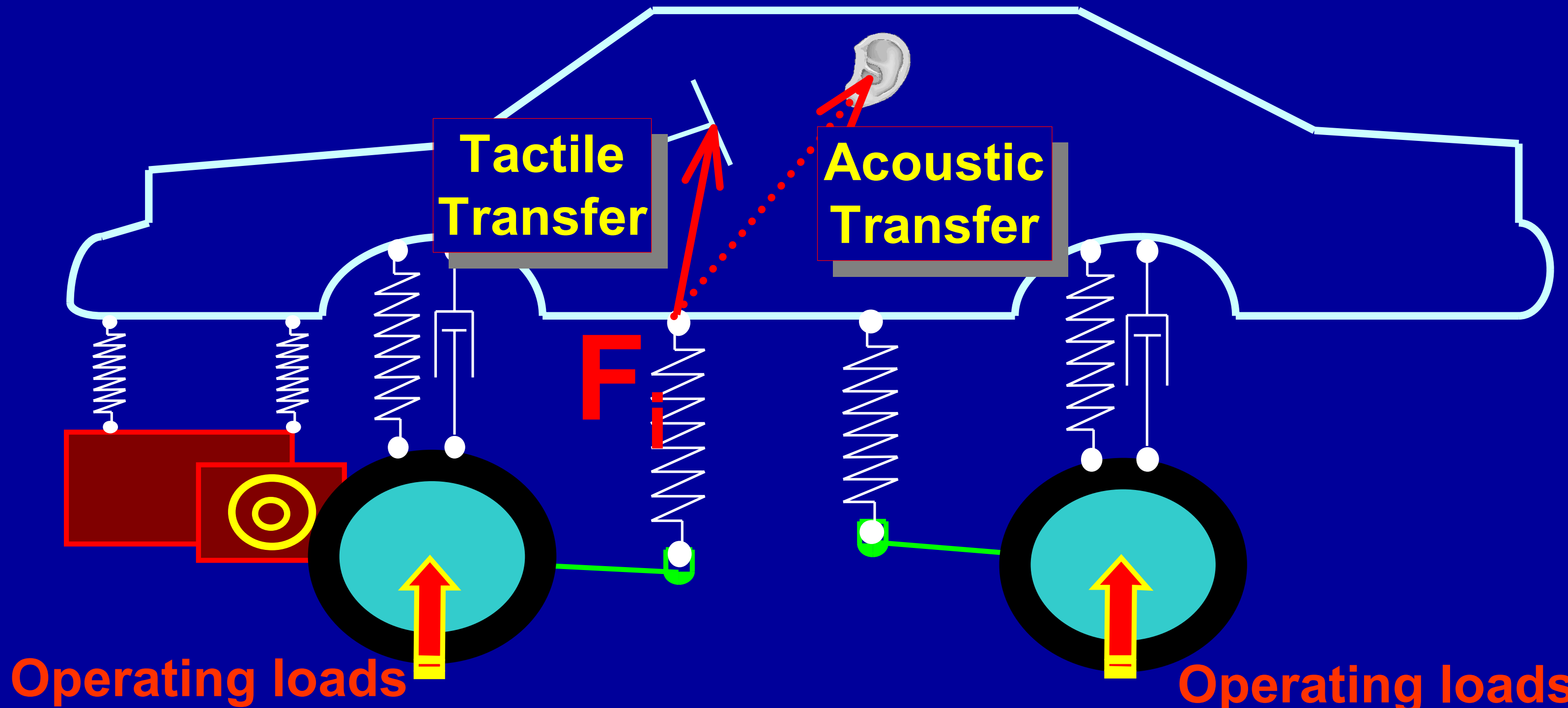
Effective Isolation

&

Identifying Key Noise Paths

Identifying Key Noise Paths

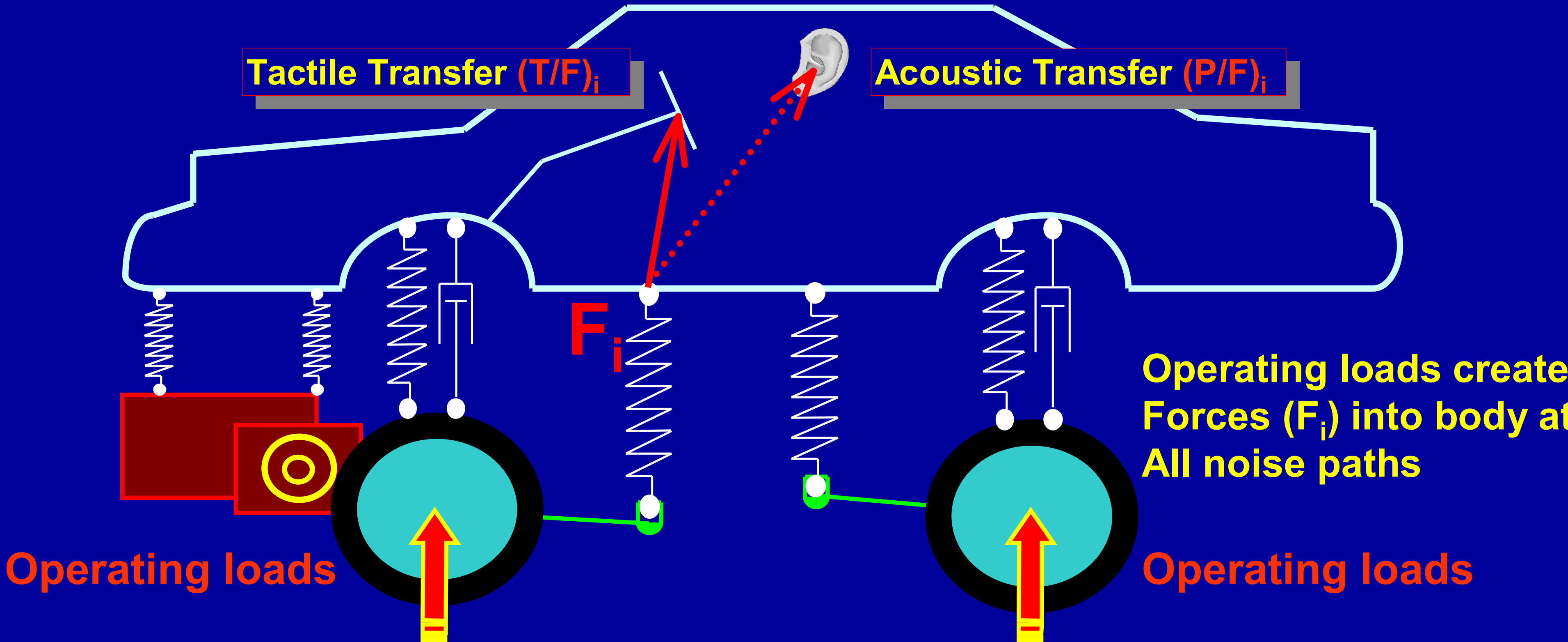
- **Key noise paths identified by Transfer Path Analysis (TPA)**



- **TPA is a technique to perform phased summation of partial responses through all noise paths to give total tactile or acoustic response under operating loads at a given frequency**

- **TPA is applicable in both testing and simulation scenarios to identify key noise paths**

Transfer Path Analysis



- Total operating Response (Tactile/Acoustic) is summation of partial responses through all noise paths

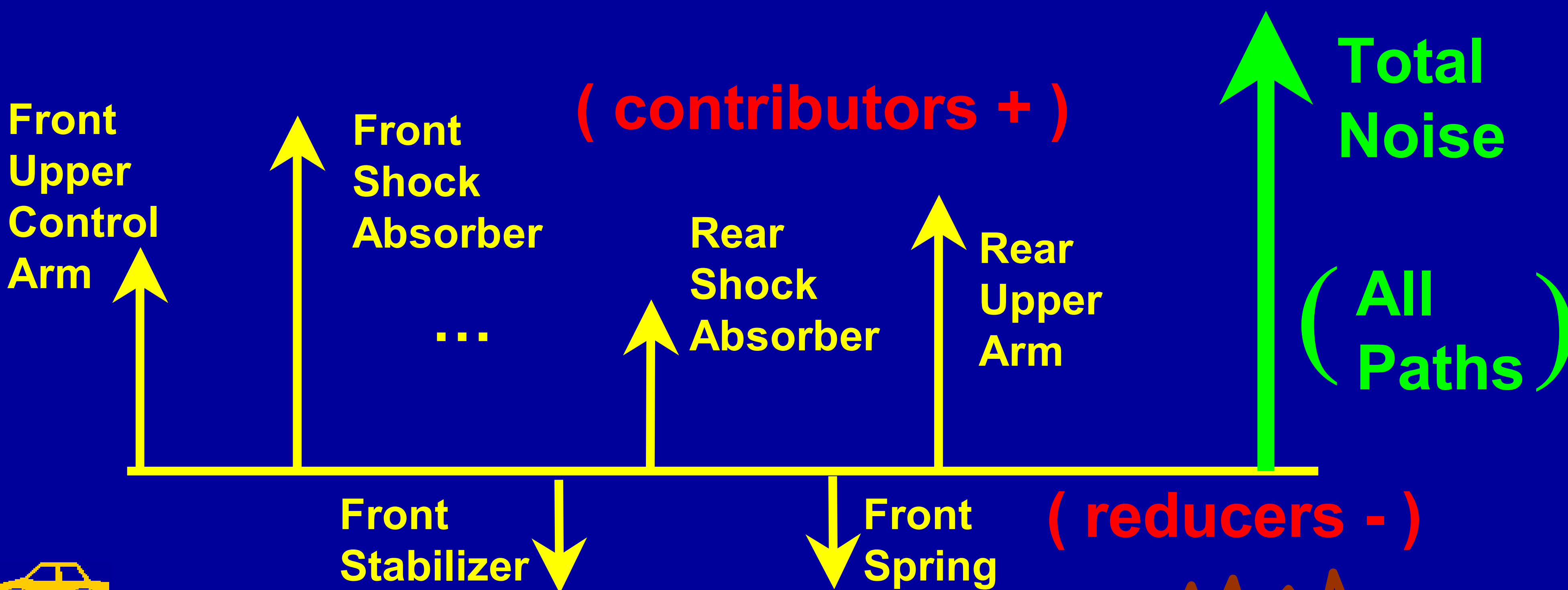
$$R_t = \Sigma_{paths} [R_i] = \Sigma_{paths} [F_i * (R/F)_i]$$

R_i : Partial contribution of path i due to operating force

$(R/F)_i$: Tactile or Acoustic Transfer Function

Transfer Path Analysis

- TPA allows path rankings based on contribution to total response of noise paths at a given frequency
- TPA thus helps identify key noise paths
- TPA is mainly used for acoustic response in mid frequency range



Designing for Mid Frequency

- **Important characteristics of mid frequency analysis**

Effective Isolation

&

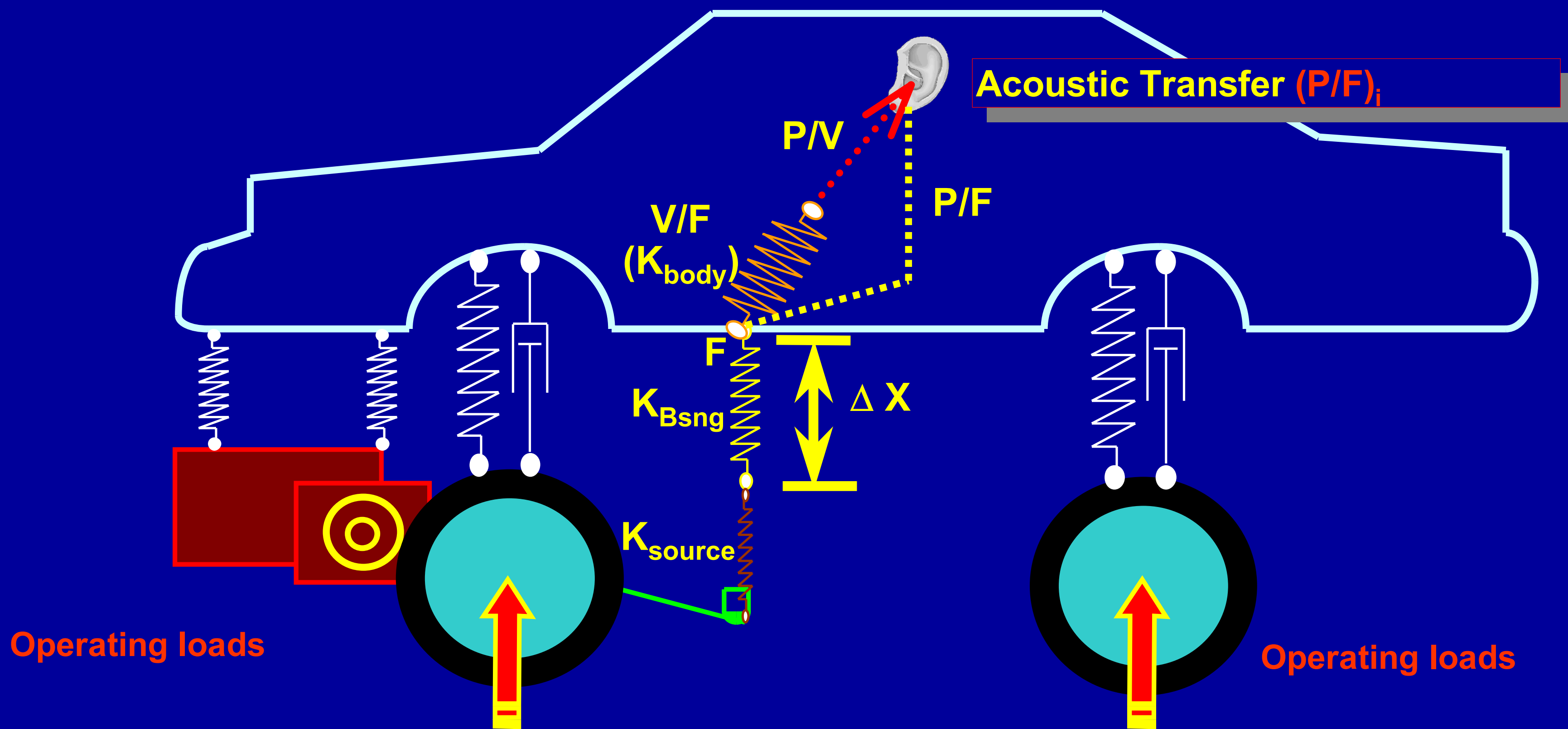
Identifying Key Noise Paths

Designing for Mid Frequency

While designing a new vehicle, generic targets are set for key parameters along *all noise paths* in order to achieve effective isolation.

What are these generic targets and key parameters ?

Generic Noise Path Targets



Transmissibility along a given noise path (TR_i)

$$TR = \left| (Y_r + Y_s) / (Y_i + Y_r + Y_s) \right|$$

$$TR = \left| \left(\frac{1}{K_{body}} + \frac{1}{K_{source}} \right) \Big/ \left(\frac{1}{K_{body}} + \frac{1}{K_{iso.}} + \frac{1}{K_{source}} \right) \right|$$

Generic Noise Path Targets

$$TR = \left| \left(\frac{1}{K_{body}} + \frac{1}{K_{source}} \right) \Big/ \left(\frac{1}{K_{body}} + \frac{1}{K_{iso.}} + \frac{1}{K_{source}} \right) \right|$$

$K_{body.}/K_{iso}$ ↓ \ $K_{source.}/K_{iso}$ →	1.0	5.0	Infinite
1.0	0.67	0.54	0.50
5.0	0.54	0.28	0.17
Infinite	0.50	0.17	0.00

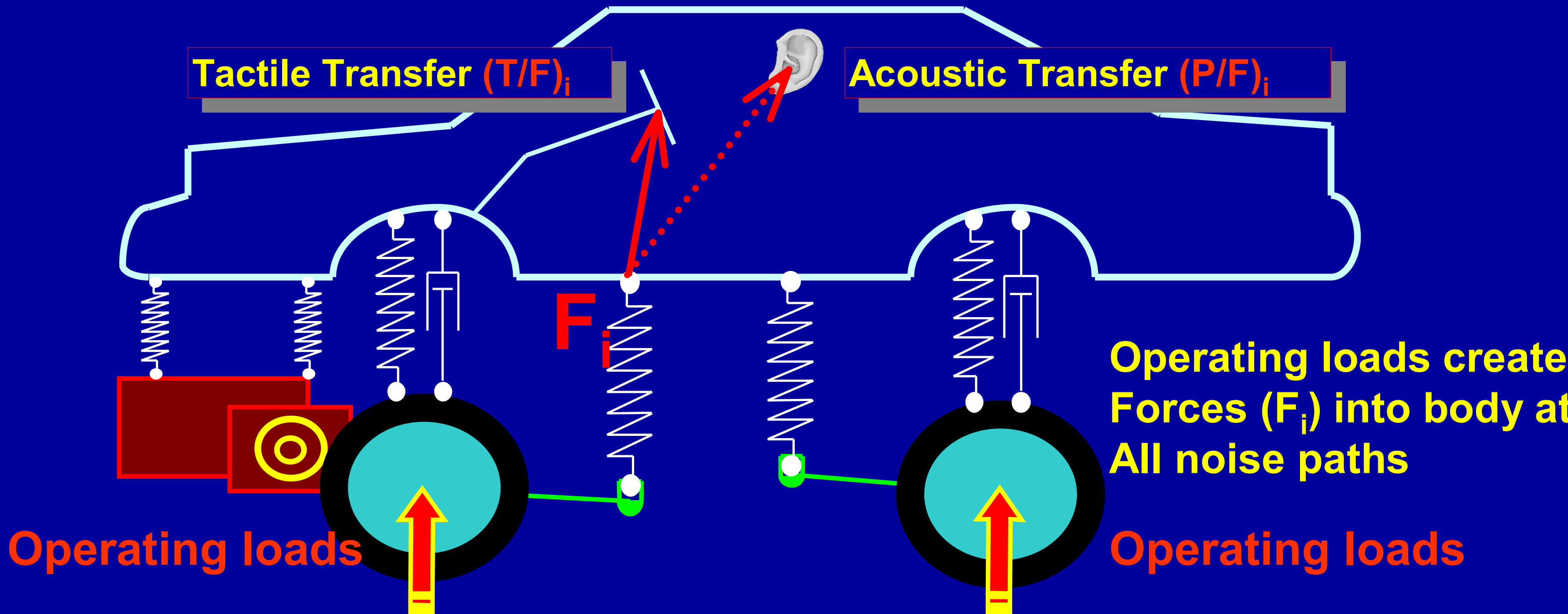
As a generic target, body to bushing stiffness ratio of at least 5.0 and very high source to bushing stiffness ratio (~ infinite) is desired to achieve "good" TR of 0.17

Relationship of Body-to-Bushing Stiffness ratio to Transmissibility

For infinitely stiff (immobile) source

$$TR = \left| (K_{bsg}) / (K_{bsg} + K_{body}) \right|$$

Generic Noise Path Targets



$$R_t = \Sigma_{paths} [R_i] = \Sigma_{paths} [F_i * (R/F)_i]$$
$$= \Sigma_{paths} [F_i * (R/V)_i * (V/F)_i]$$

Response R_t could be either Tactile or Acoustic Response

Generic Noise Path Targets

For example, for Acoustic Response P_t

$$P_t = \Sigma_{paths} [P_i] = \Sigma_{paths} [F_i * (P/F)_i] = \Sigma_{paths} [F_i * (P/V)_i * (V/F)_i]$$

- For a given force generated at suspension attachment to body, lowering sensitivities (P/F) or (V/F) along a path would reduce total response
- As a generic target,
  - Acoustic sensitivity (P/F) in 55-60 dBL/N range
  - Structural Mobility (V/F) less than 0.312 mm/sec/N

Generic Noise Path Targets

How does one achieve these generic targets :

$$\frac{K_{body}}{K_{iso}} >= 5.0$$

$$\frac{K_{source}}{K_{iso}} \sim \text{infinite}$$

55 dBL/N < Acoustic Mobility < 60 dBL/N

Structural Mobility < 0.312 mm/sec/N

Generic Noise Path Targets

How does one achieve

$$\frac{K_{body}}{K_{iso}} >= 5.0$$

Structural Mobility < 0.312

- Increase local body attachment stiffness (K_{body}) through structural modifications

- Reduce attachment isolator stiffness (K_{iso}) while balancing the conflicting requirement of other functionalities such as Ride & Handling

Generic Noise Path Targets

How does one achieve

$$\frac{K_{source}}{K_{iso}} \sim \text{infinite}$$

- Increase source side attachment stiffness (K_{source})
- Reduce attachment isolator stiffness (K_{iso})

In automotive structures, it is realistic to expect that source to isolator stiffness ratio is almost infinite since source usually corresponds to stiff structure (such as powertrain or axle)

Source Excitation Characteristics

Other means of reducing source input to paths

- Add lumped mass on component
- Use tuned absorber

Applicable when Rigid Body Resonance of Source Side Component are present

- Bring nodal points toward path

Applicable when flexible modes of source side component are present

Generic Noise Path Targets

How does one achieve

$$55 < \text{Acoustic Mobility} < 60$$

- At a given frequency, Acoustic Mobility (P/F) is

$$P/F = (P/V) \times \frac{\text{Frequency}}{\text{Body stiffness}}$$

- Based on the above equation, increasing body stiffness usually reduces acoustic mobility

Generic Noise Path Targets

How does one achieve

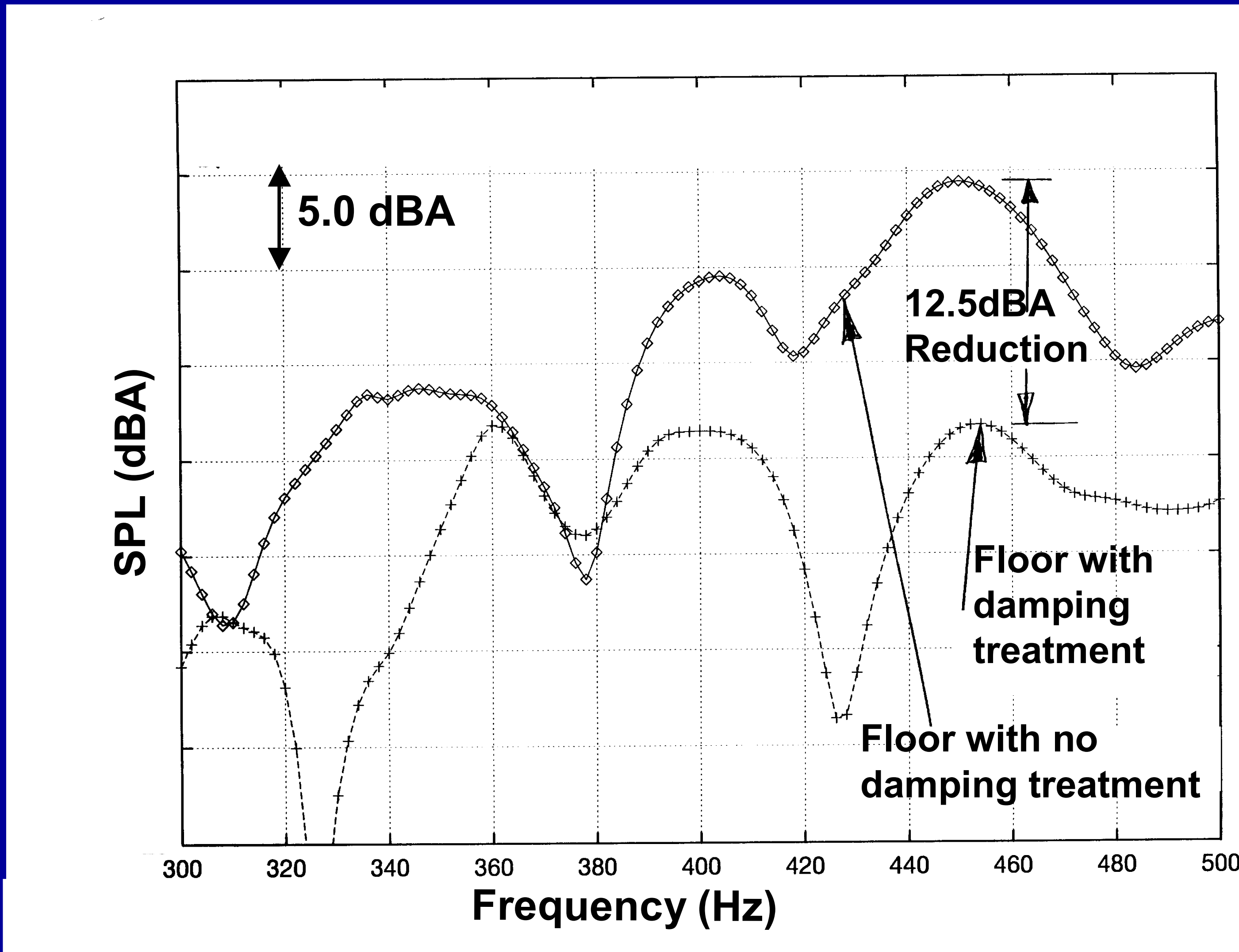
55 < Acoustic Mobility < 60

- There are situations when increasing body stiffness does not reduce acoustic mobility

- In such cases, means of reducing acoustic mobility are to reduce overall body panel velocity through application of damping and acoustic treatment

Application of Damping Treatment

Effect on sound response of damping treatment applied on key identified contributing panels



[Figure Courtesy of DaimlerChrysler Corporation]

Designing for Mid Frequency

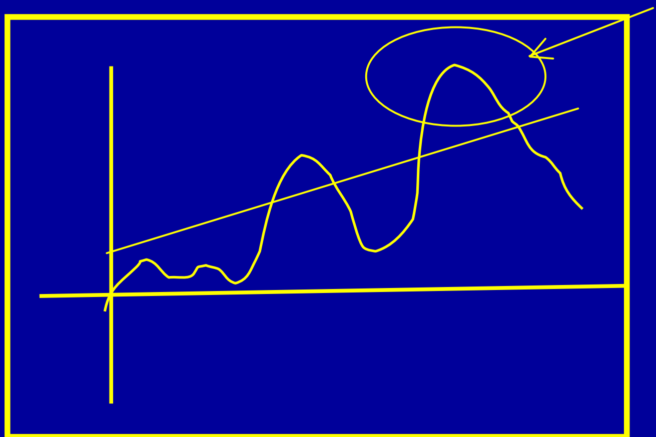
While designing a new vehicle, generic targets are set for key parameters along *all noise paths* in order to achieve effective isolation.

is it really necessary to achieve generic targets for all noise paths ?

Probably Not !!

Designing for Mid Frequency

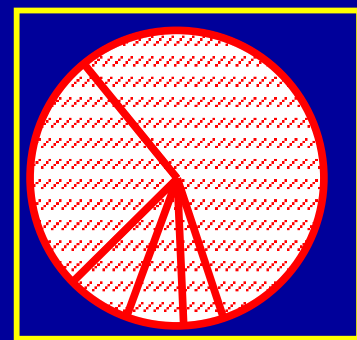
Driver's Ear Noise



Vehicle Level Response

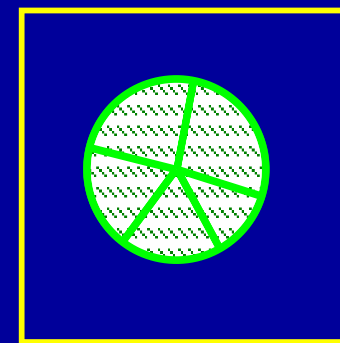
Transfer Path Analysis

Original Noise Path Contributions



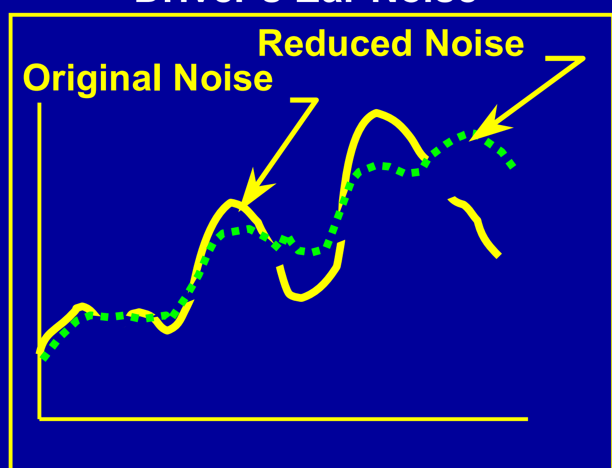
Some noise paths are more dominant than others

Original Noise Path Contributions



Impose more strict requirements for these dominant paths and relax requirements for other paths to achieve more "rebalanced" noise

Driver's Ear Noise



Vehicle Response to Meet NVH Targets

Designing for Mid Frequency

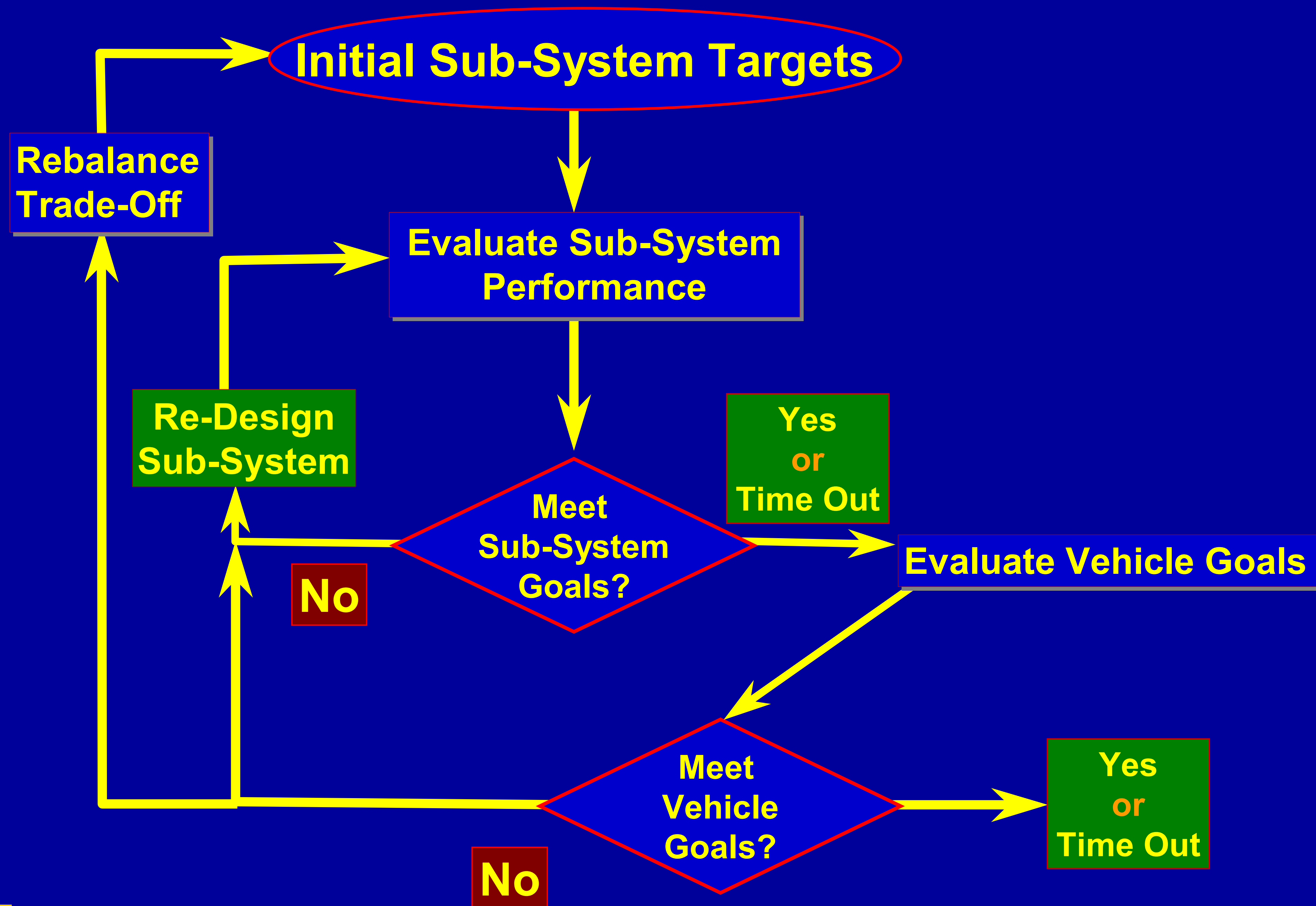
Principles to follow

- At the beginning of program, work towards generic targets for key parameters for all noise paths in order to achieve effective isolation.

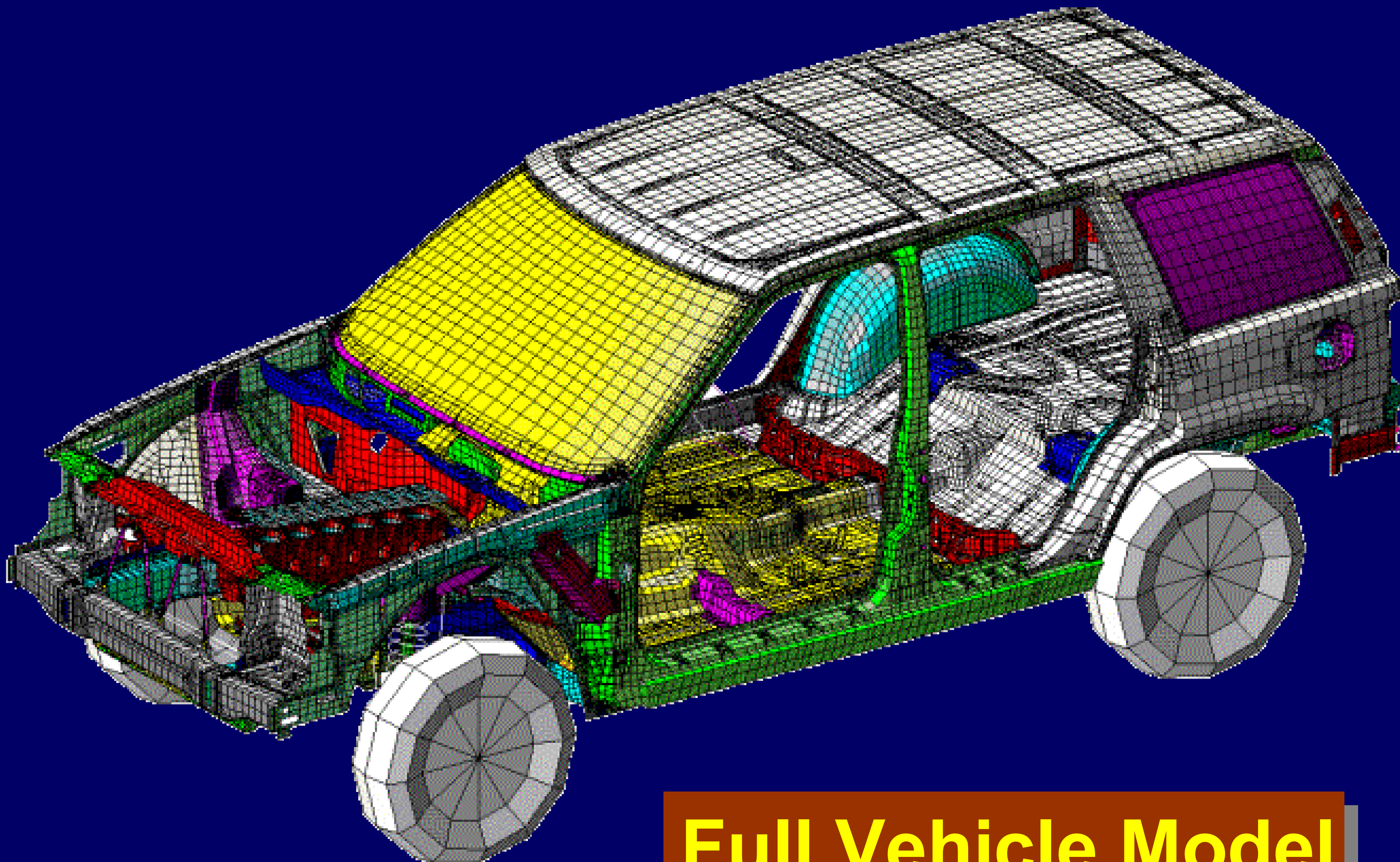
- As the design is firmed out, evaluate key noise paths using Transfer Path Analysis in order to meet target for all NVH operating load conditions.

- Perform path "rebalancing" to arrive at revised path targets (more strict for dominant paths) for all NVH operating load conditions.

Mid Frequency NVH Goal Achievement Process



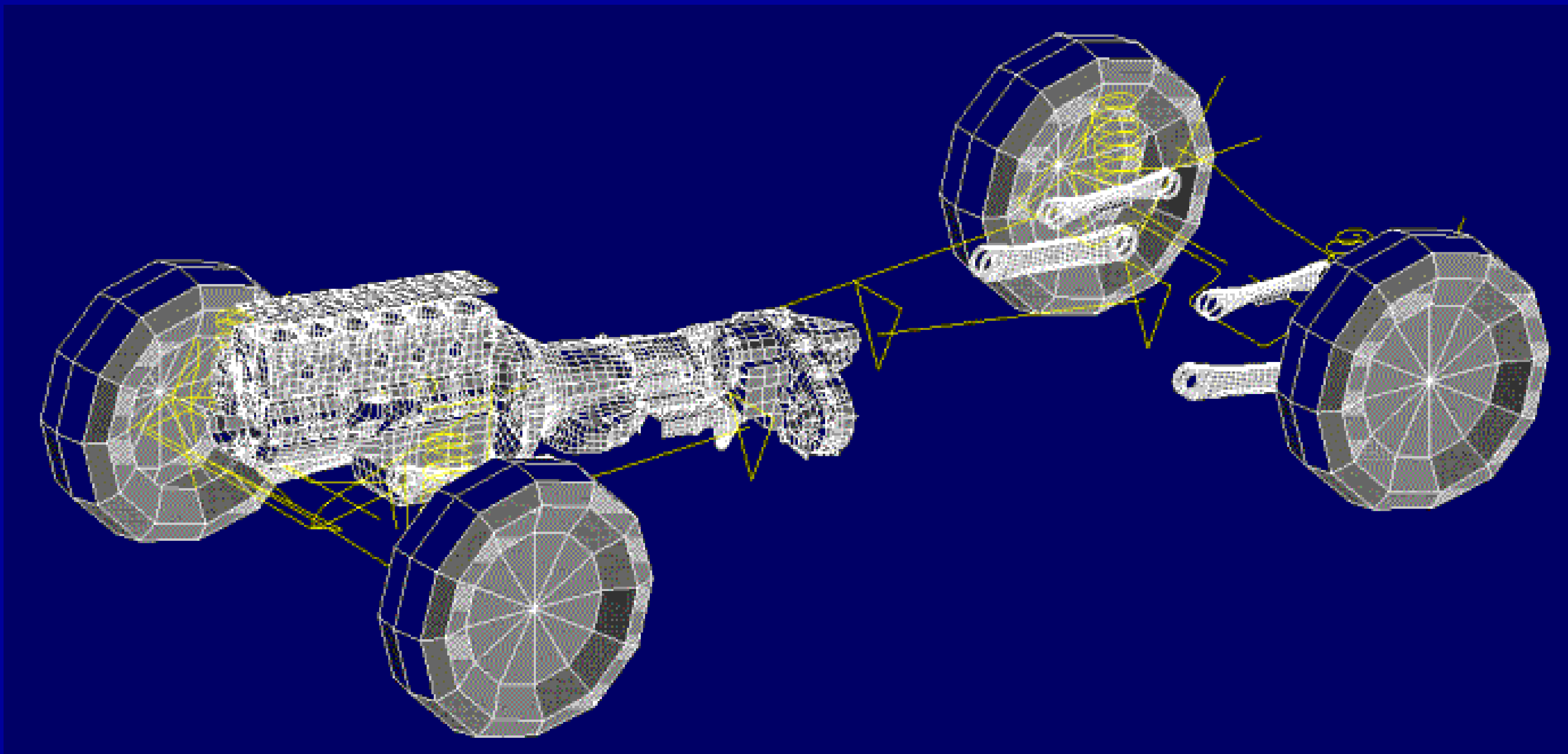
Mid Frequency NVH Improvement
(Sports Utility Vehicle Example)



Full Vehicle Model

[Figure Courtesy of DaimlerChrysler Corporation]

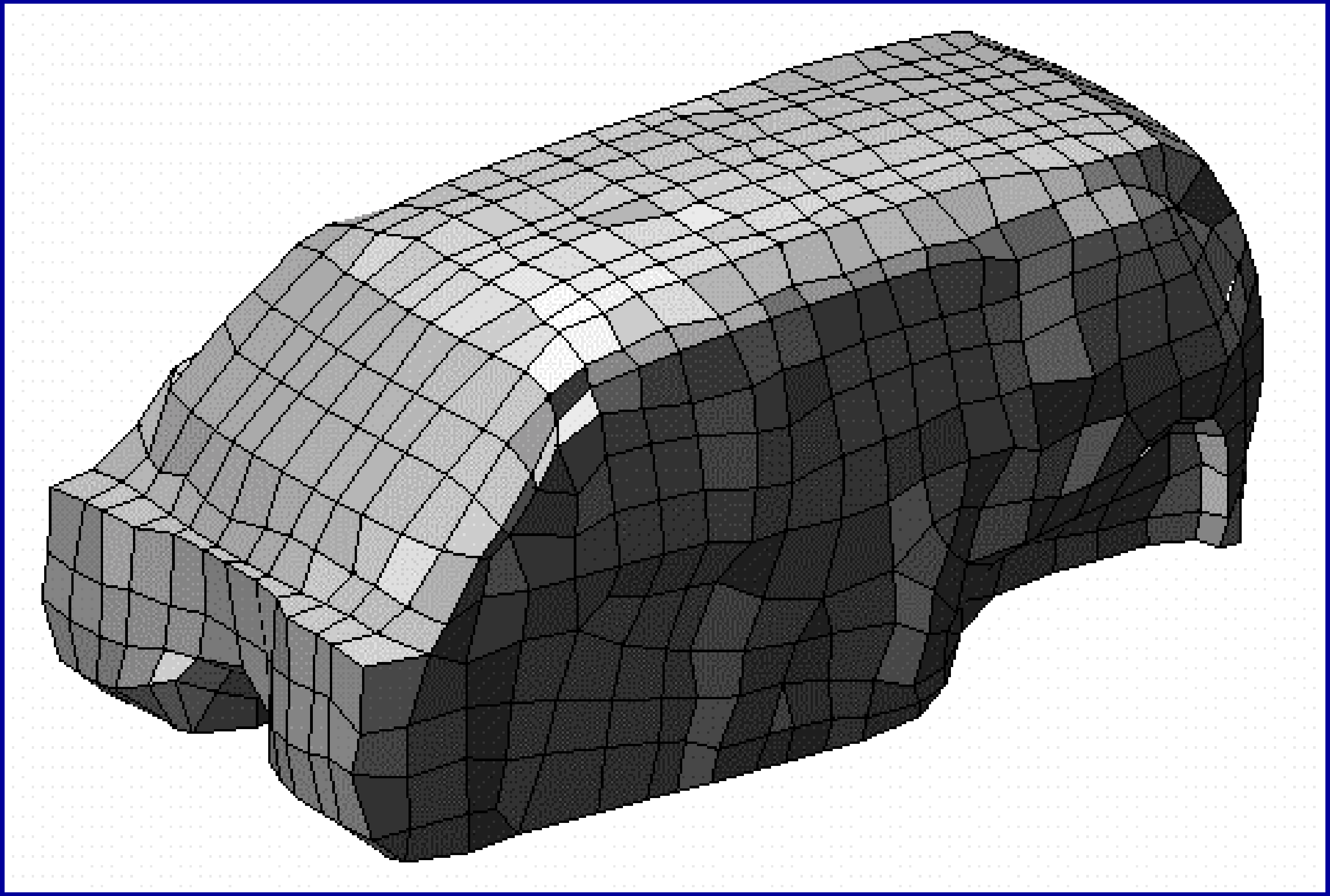
Mid Frequency NVH Improvement
(Sports Utility Vehicle Example)



Powertrain/Axle/Suspension Model

[Figure Courtesy of DaimlerChrysler Corporation]

Mid Frequency NVH Improvement
(Sports Utility Vehicle Example)



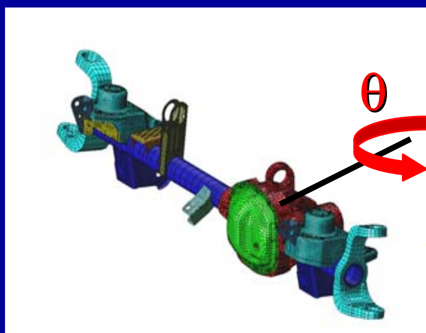
Acoustic Cavity Model

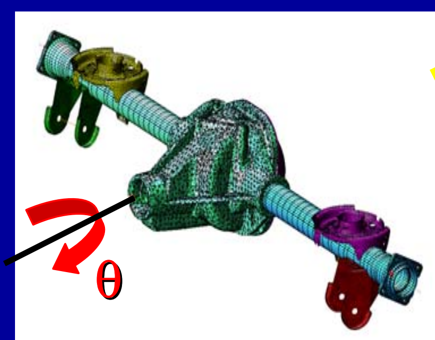
[Figure Courtesy of DaimlerChrysler Corporation]

Mid-Frequency NVH improvement

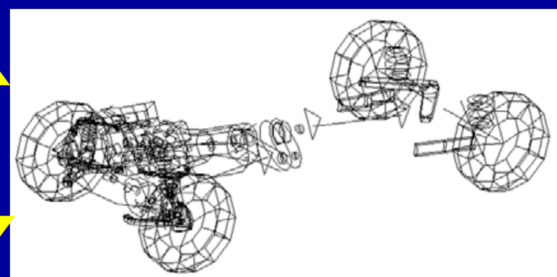
Axle Whine Example : 300-500 Hz

Front and Rear Axle
Gear-Pinion Mesh
Transmission Error

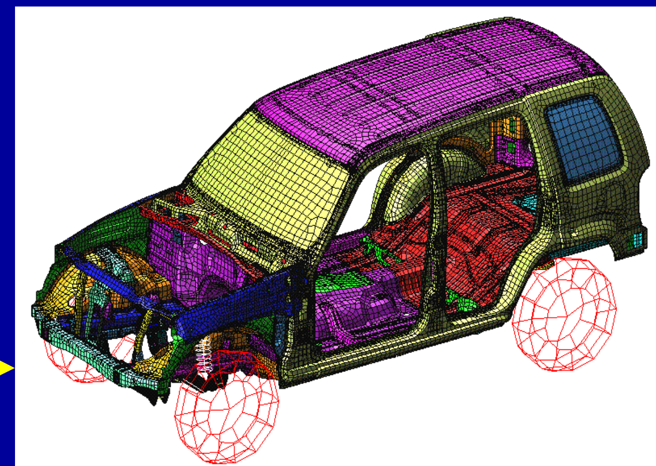


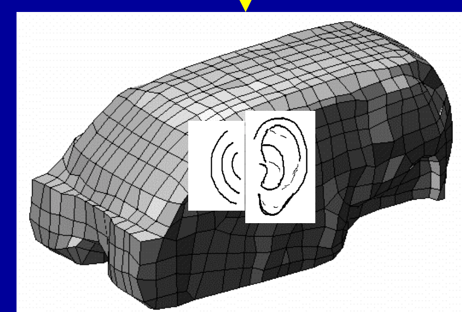


Chassis



Trimmed Body





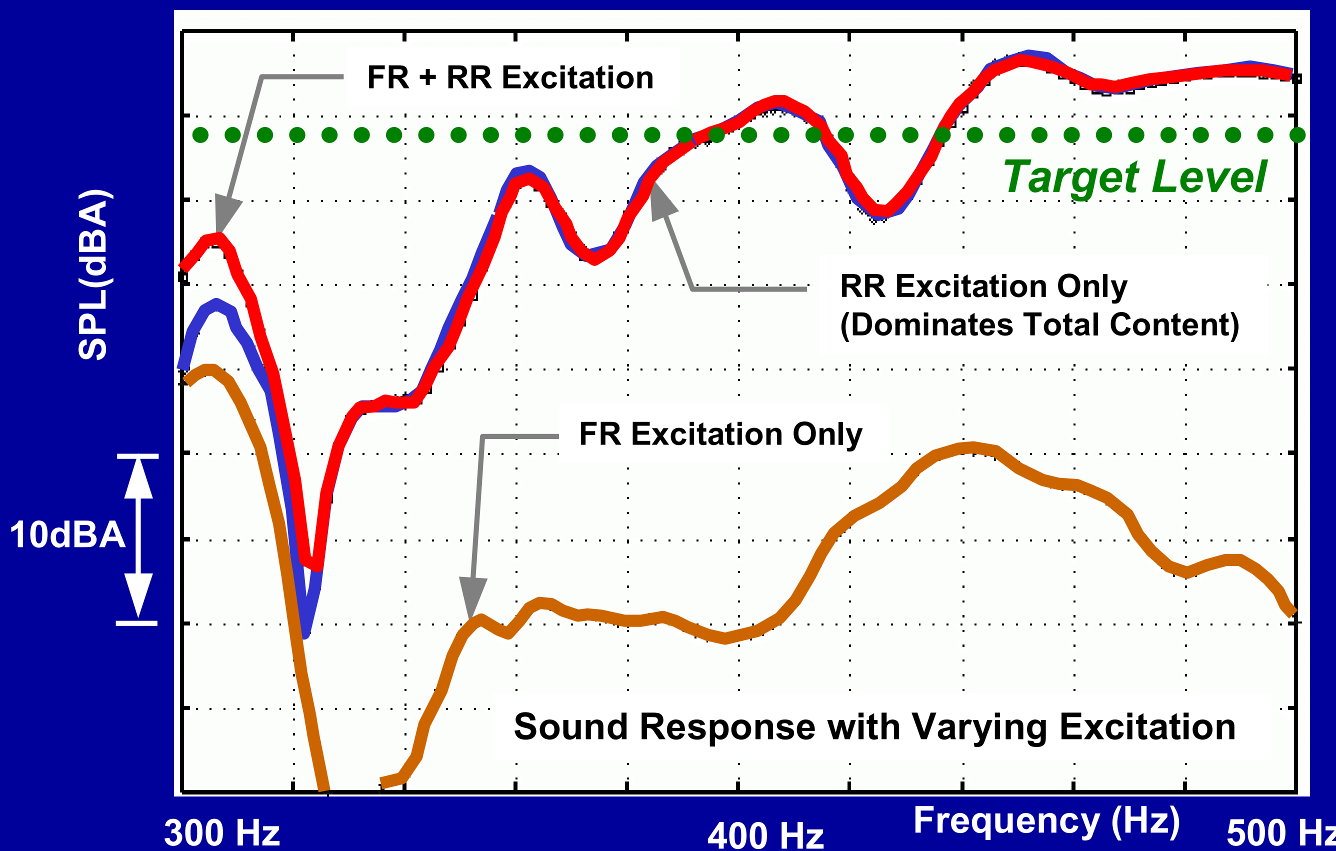
Interior Acoustic Cavity

SOURCE ------------- PATH --------------- RECEIVER

[Figure Courtesy of DaimlerChrysler Corporation]

Axle Whine Example

- Design work was focused in the beginning towards achieving generic targets for all noise paths
- As the design was firmed out, full vehicle analysis revealed under target performance for Driver's ear SPL response which was dominated by rear excitation



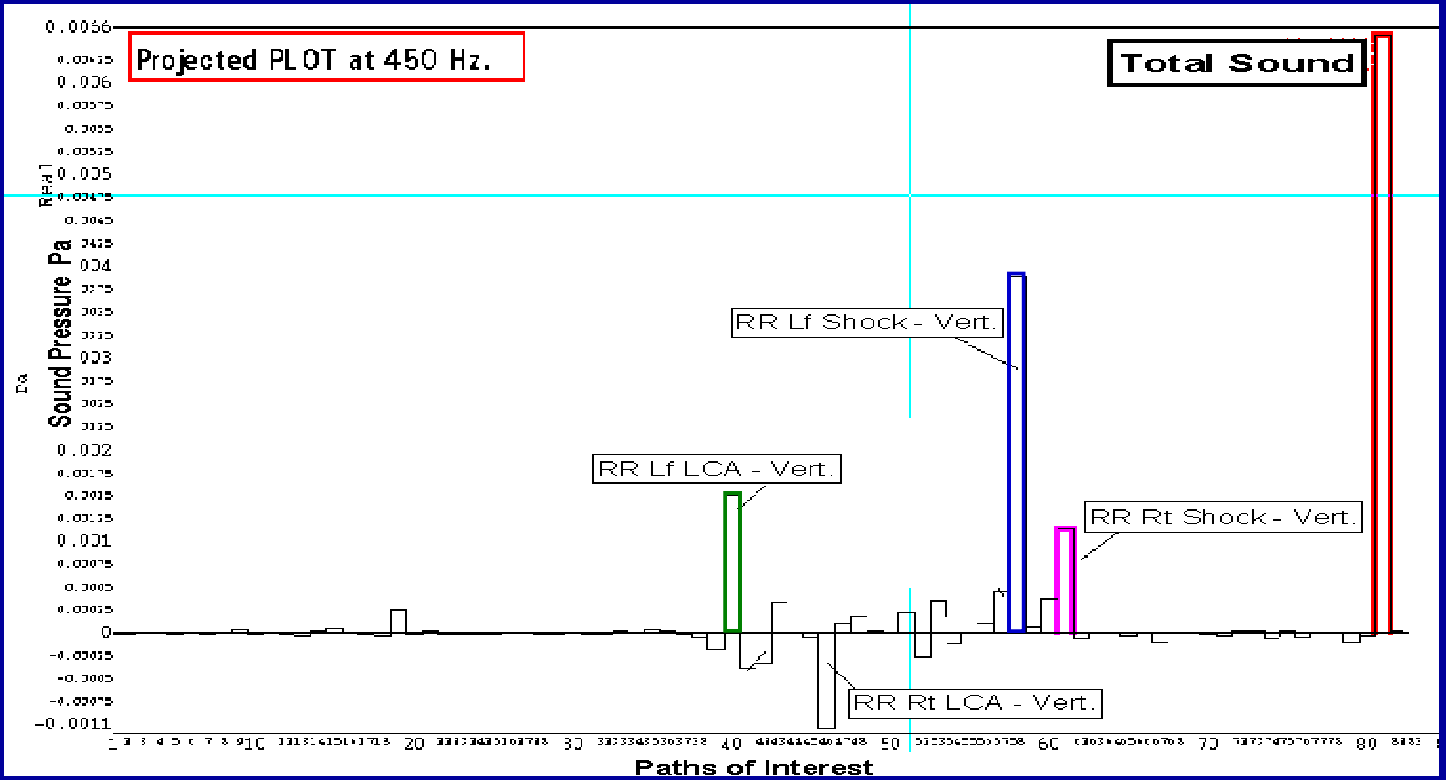
[Figure Courtesy of DaimlerChrysler Corporation]

Axle Whine Example

- Before embarking on identifying the root cause for under-target performance at dominant noise paths, it is a good practice to perform reasonableness check on the response
- Steps for Reasonableness Determination
  - ➢ Judging the response based on system knowledge
    - Total response content is dominated by rear excitation. This is reasonable since vehicle has IFS and solid axle rear suspension which is harder to isolate for noise
  - ➢ Forced mode Animation
    - Operating deformed shape motion is rear axle pitching about ring gear axis. This was expected since input excitation is MTE imposed as enforced angular rotation between ring and pinion gear
  - ➢ Disconnect Studies
    - Disconnecting rear suspension noise paths (shock in particular) in pair had the most significant effect on Driver's SPL response

Axle Whine Example

- Transfer Path Analysis



- Dominant Paths
  - Rear left shock vertical
  - Rear LCA vertical : Left is positive whereas right is negative contributor
  - Rear Right shock vertical

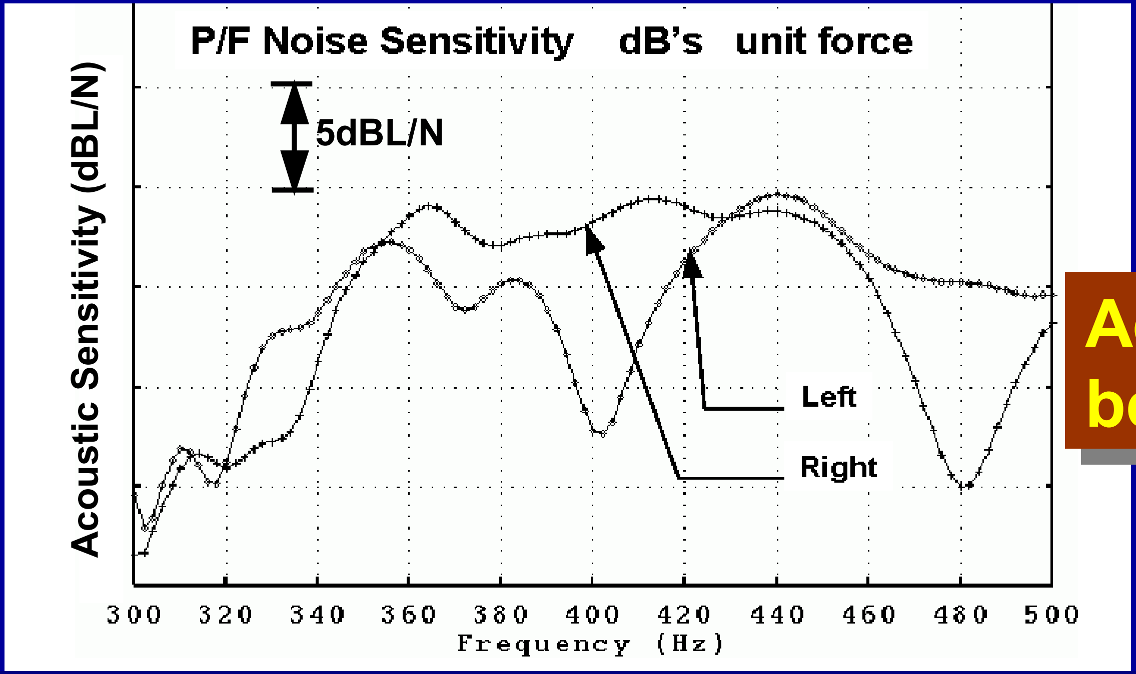
- The conclusion matches with reasonableness checks

[Figure Courtesy of DaimlerChrysler Corporation]

Axle Whine Example

- Is it high forces or high acoustic sensitivity at shock to body attachment ?

$$R_t = \Sigma_{paths} [R_i] = \Sigma_{paths} [F_i * (R/F)_i]$$



Acoustic sensitivity is better than generic target

- The issue is with high forces into the body through shock attachment due to stiff shock bushings
- Stiff shock bushings gave low body-to-bushing stiffness ratio

[Figure Courtesy of DaimlerChrysler Corporation]

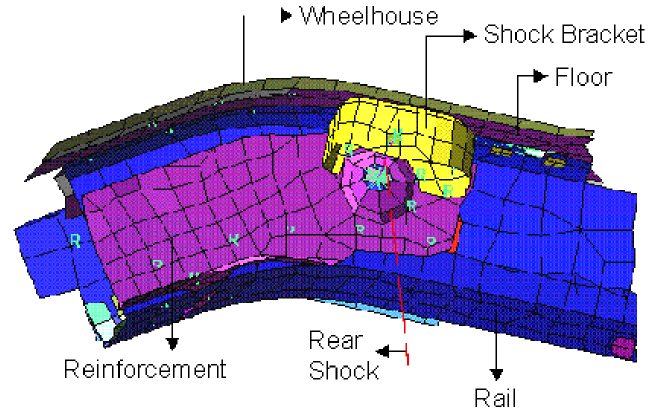
Axle Whine Example

Solution

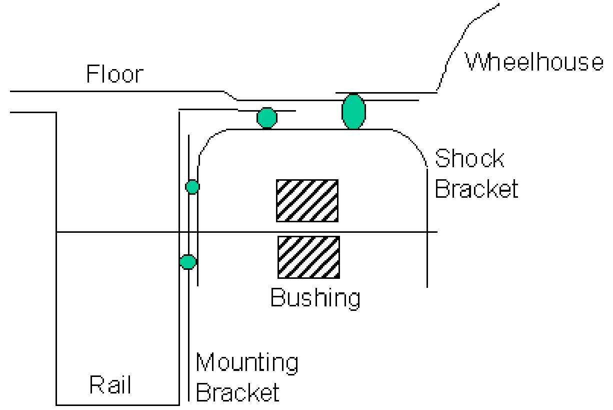
- Soften shock vertical bushings by 65%

- To balance this against handling requirement of stiff bushing, local attachment stiffness between shock and body was improved through a new bracket design

- This addition of bracket improved right shock mobility 3 times whereas left shock mobility by 1.5 times thereby improving isolation effectiveness of shock bushing



Configuration of Shock Bracket

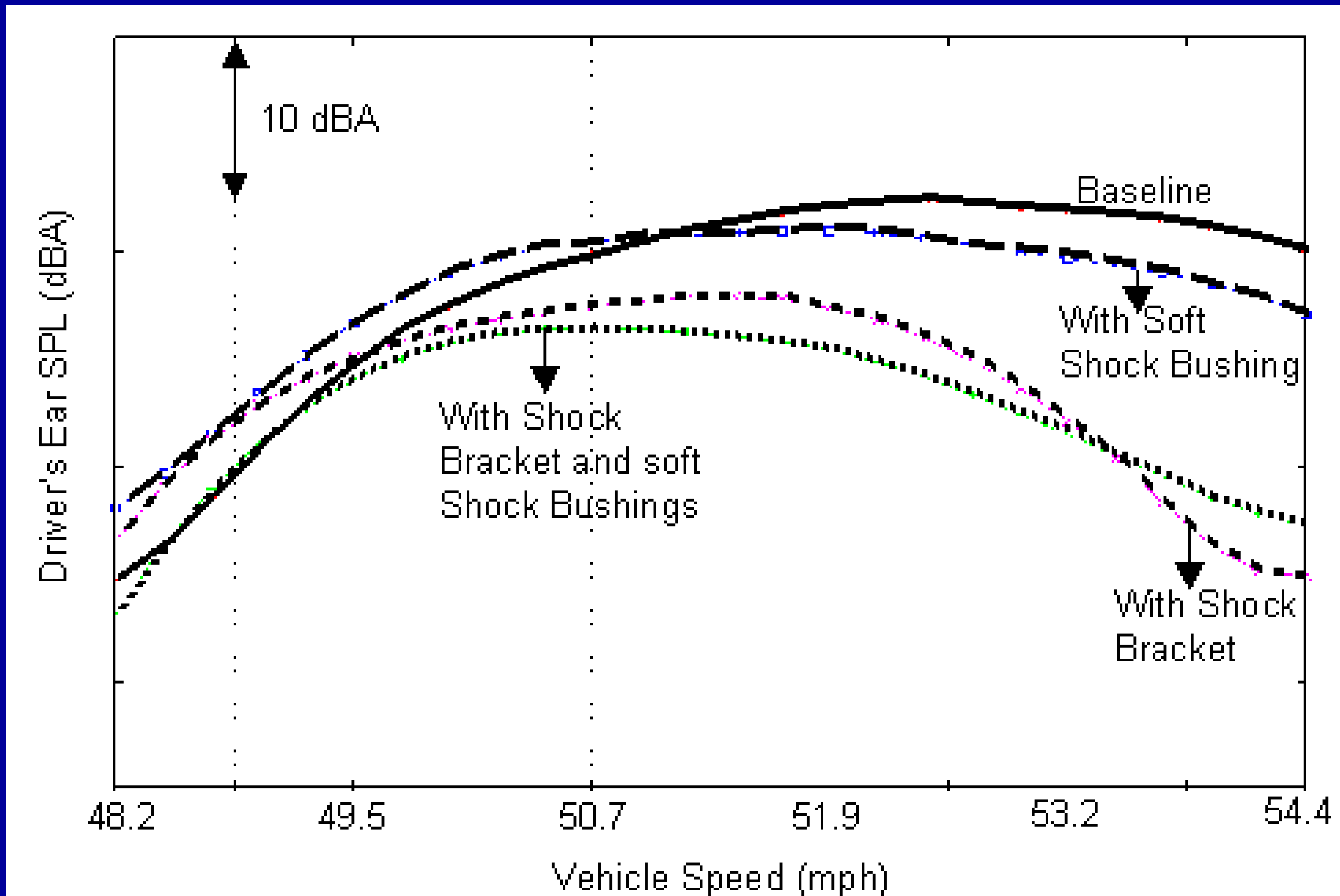


Rear View Section of Shock Bracket

[Figure Courtesy of DaimlerChrysler Corporation]

Axle Whine Example

Response Improvement due to proposed solution



[Figure Courtesy of DaimlerChrysler Corporation]

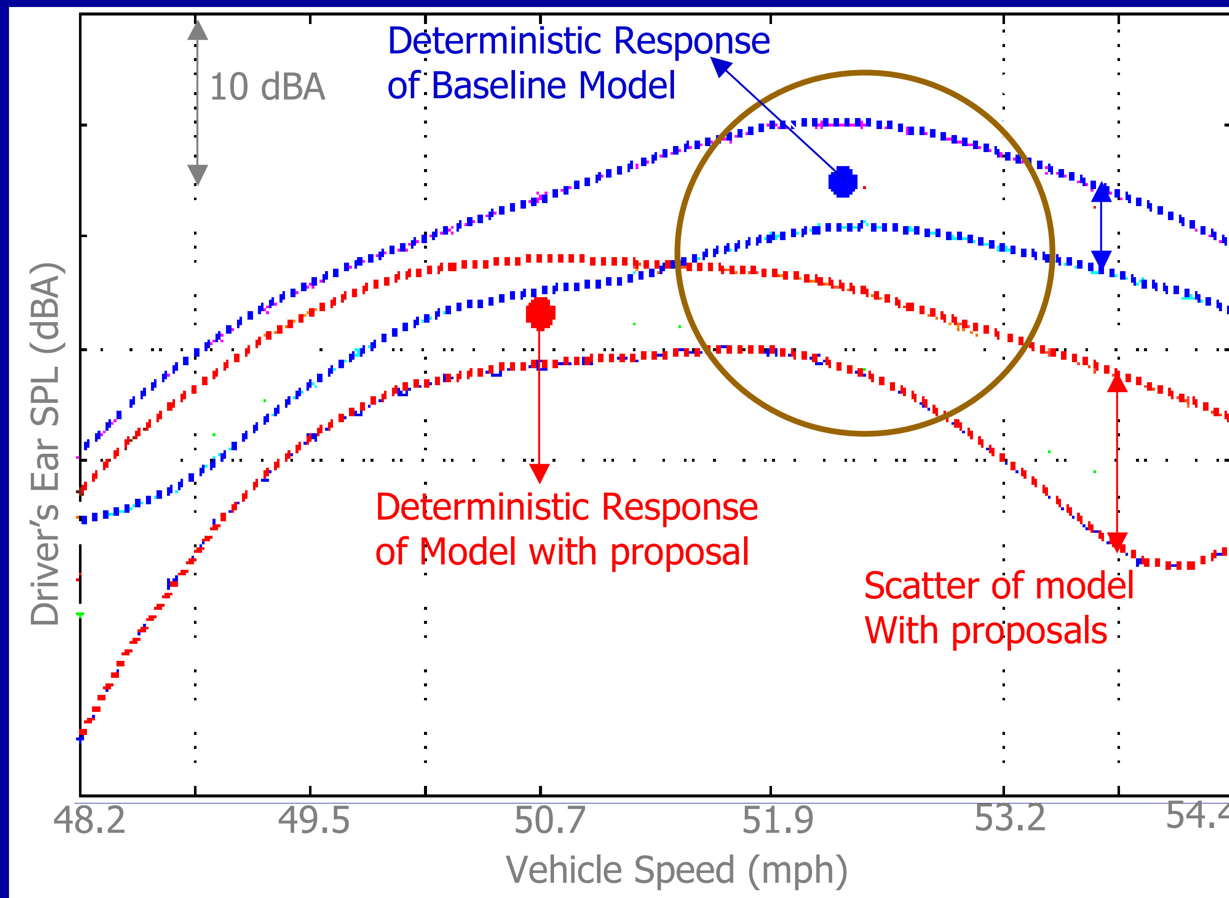
Axle Whine Example

How Robust is the proposed solution ?

- Parameter variations such as weld deletion in "new bracket" and gage changes were considered to study robustness of solution

- Response scatter of model with proposal does not overlap baseline model response scatter indicating a robust solution

- The problem peak has now shifted to a new vehicle speed of 50.7 mph which requires a new contribution analysis



[Figure Courtesy of DaimlerChrysler Corporation]

Final Remarks on Mid Frequency Analysis

- Effective isolation at dominant noise paths is critical
- Reduced mobilities at body & source and softened bushing are key for effective isolation
- Other means of dealing high levels of source input (Tuned dampers, damping treatments, isolator placement at nodal locations) are also effective
- It is important to balance NVH requirement against other functionalities (Ride and Handling, Impact)
- It is important to understand the robustness of design recommendations

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- Introduction
- Ride Balance in the Ride Range
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- Low Frequency Basics
- *Live Noise Attenuation Demo*
- Mid Frequency Basics
- **Utilization of Simulation Models**
- Closing Remarks

Alan Duncan

NVH Workshop Topic Outline

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- **Utilization of Simulation Models**

Utilizing NVH Simulation Models

Considerations

- Some Agreement: Math Models can be used as Trend Predictors.
  (but not for absolute levels, yet.)

- Q. How do I know my model is good?
- ANS. We require correlation work to know the simulation compares to test values to some degree.

- Q. How do I make design decisions before hardware is available?
- ANS. Correlation must be performed on existing hardware to establish modeling methods to be applied to the future design.
  (The Reference Baseline Ref. 3)
  A model of the new design is built with the same Methodology as the Reference Baseline to predict the change in performance as the design process progresses but before prototypes are available.

Utilizing NVH Simulation Models

Considerations

- Q. How do I compare my model to test measurement and how close does it have to be to assure it can be used as a trend predictor?
- ANS. If model predictions were within the band of variability of the test measurement, for a statistically significant number of samples, this would increase confidence in the predictive capability.

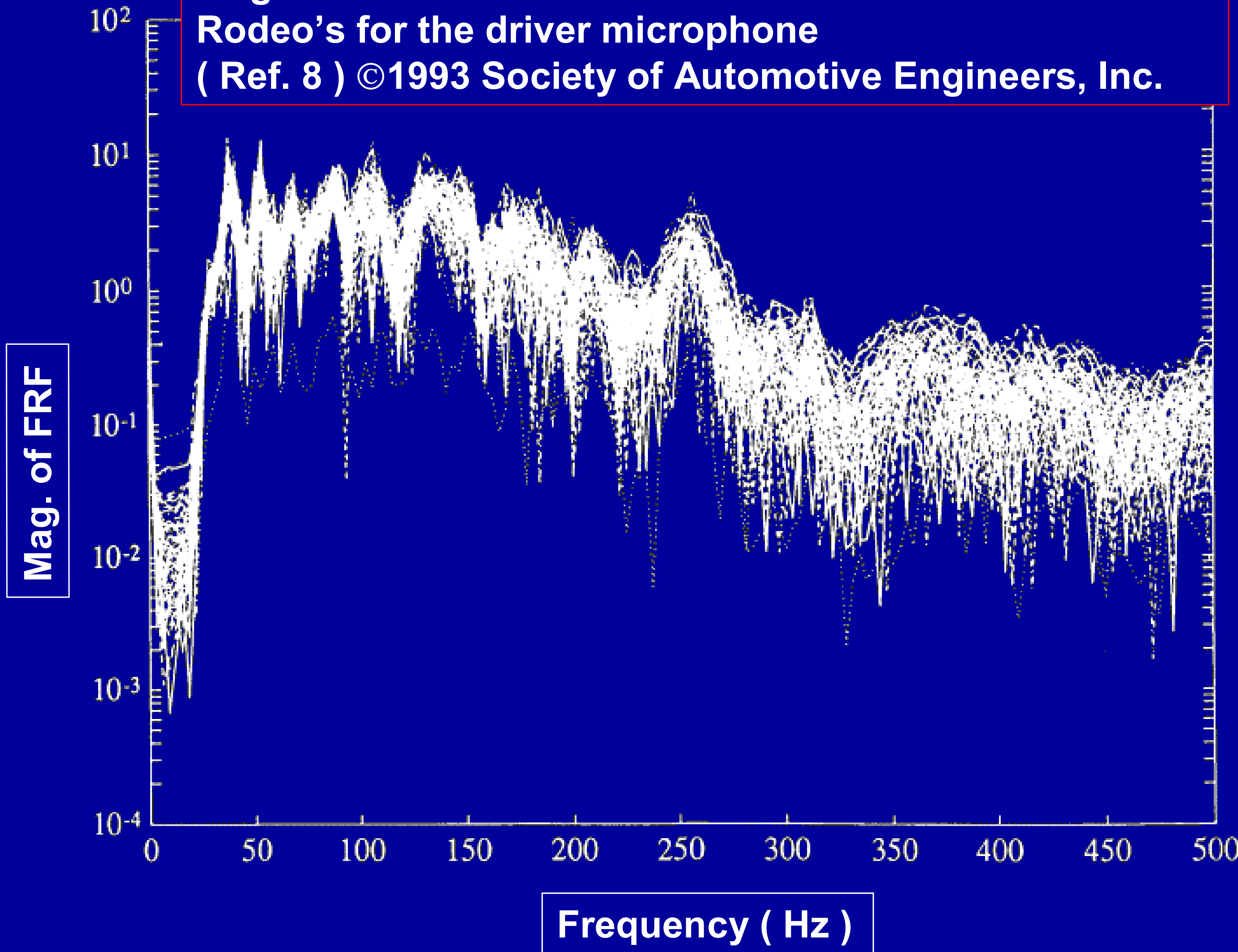
- Q. How wide is the band of variability?
- ANS. Don’t Ask !!!

Discussion of Product Variability

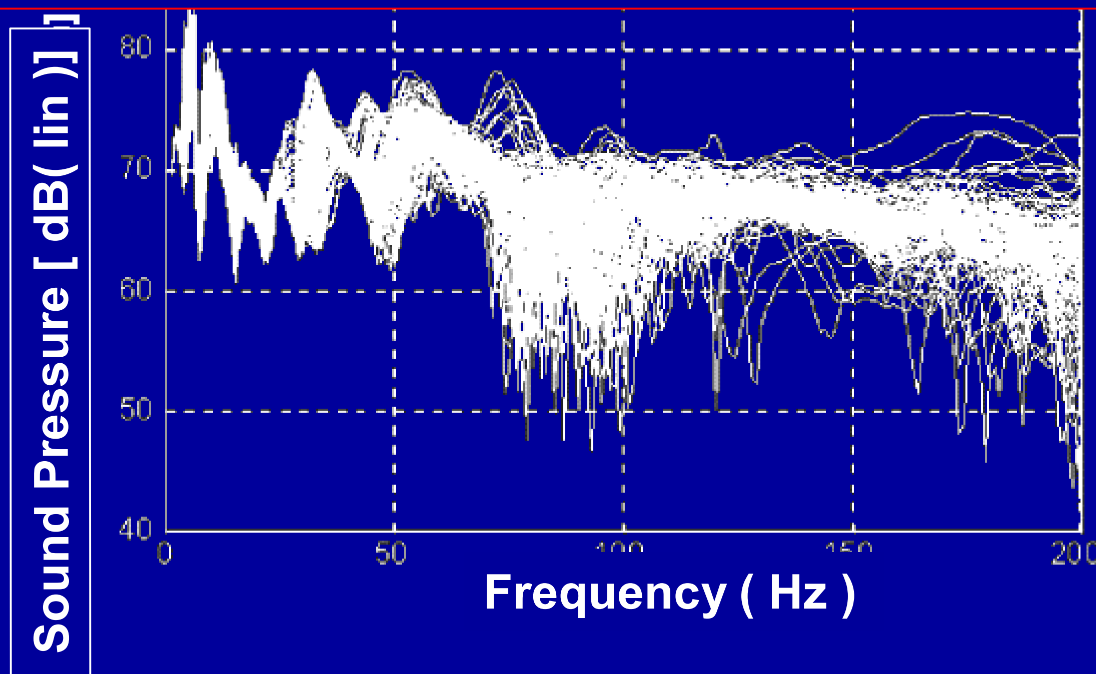
Topics

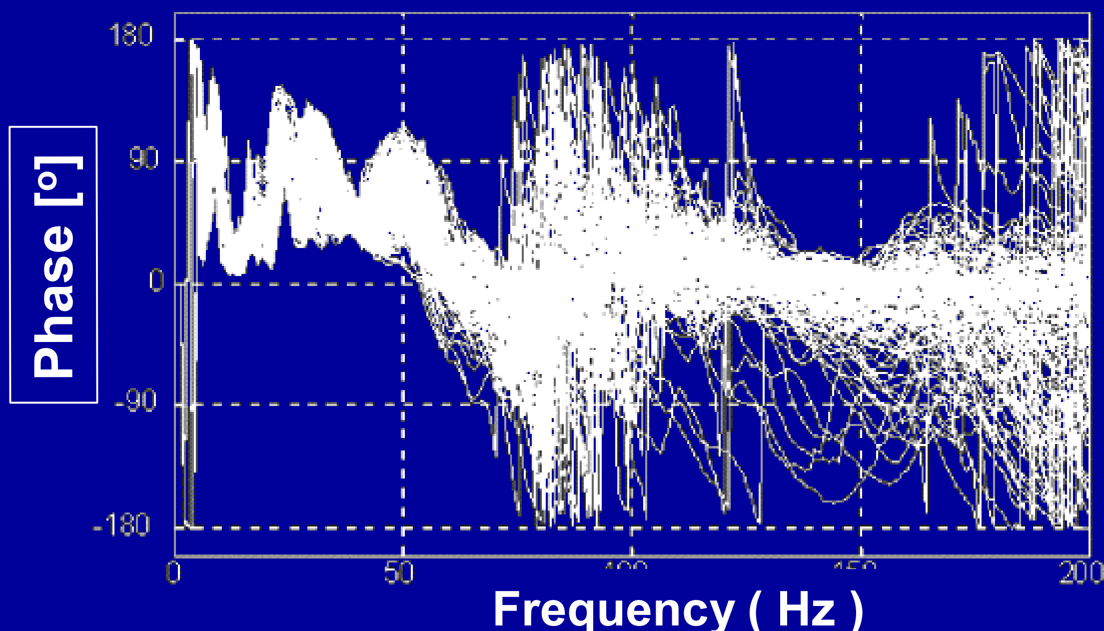
- Kompella and Bernhard Observations
- Freyman NVH Scatter Results
- Model Confidence Criteria
- Conclusions

Magnitude of 99 Structure – borne FRF's for the Rodeo's for the driver microphone (Ref. 8) ©1993 Society of Automotive Engineers, Inc.

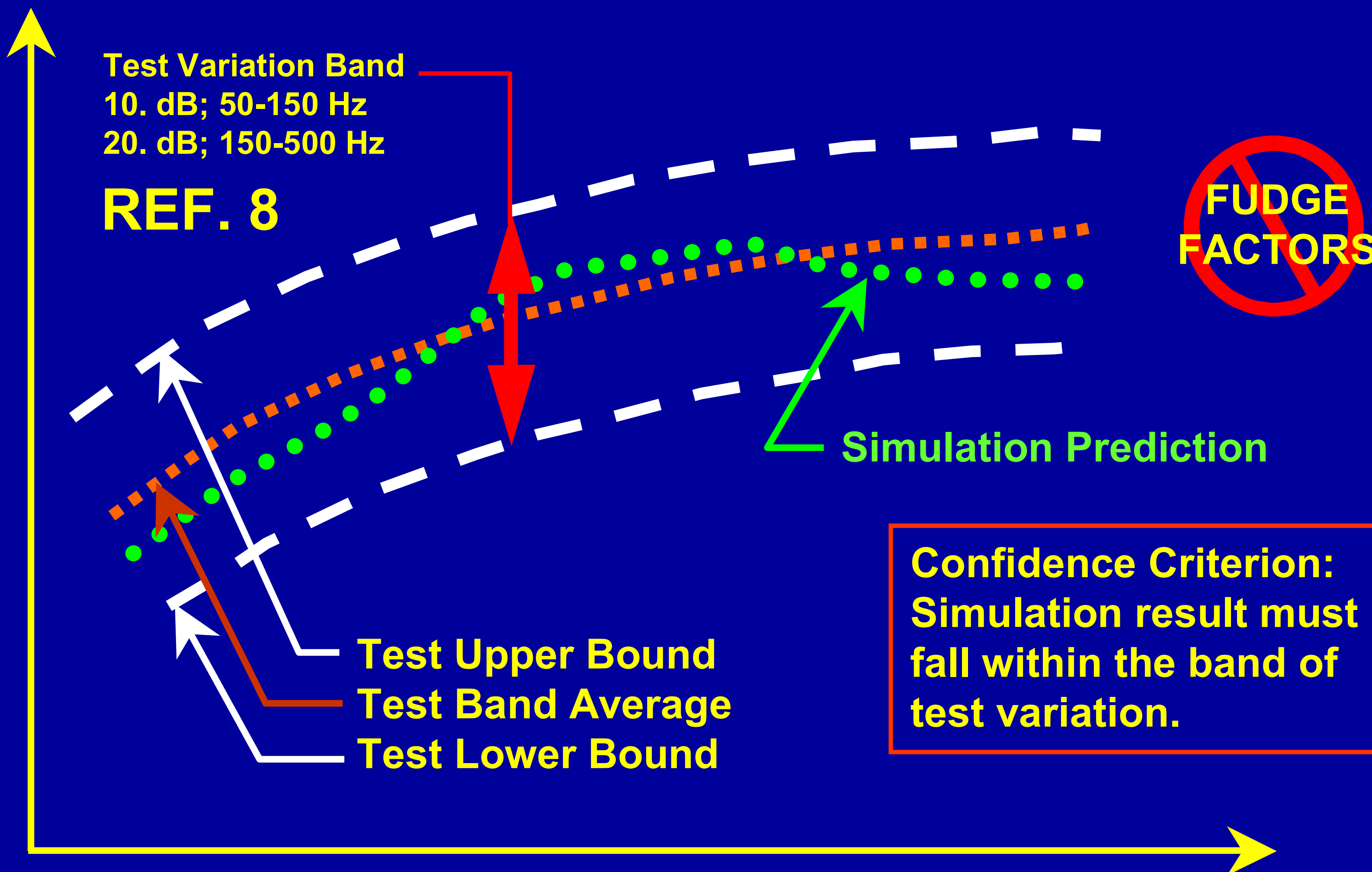


Acoustic scatter numerically determined in the vibro – acoustic behavior of a vehicle due to possible tolerances in the component area and in the production process





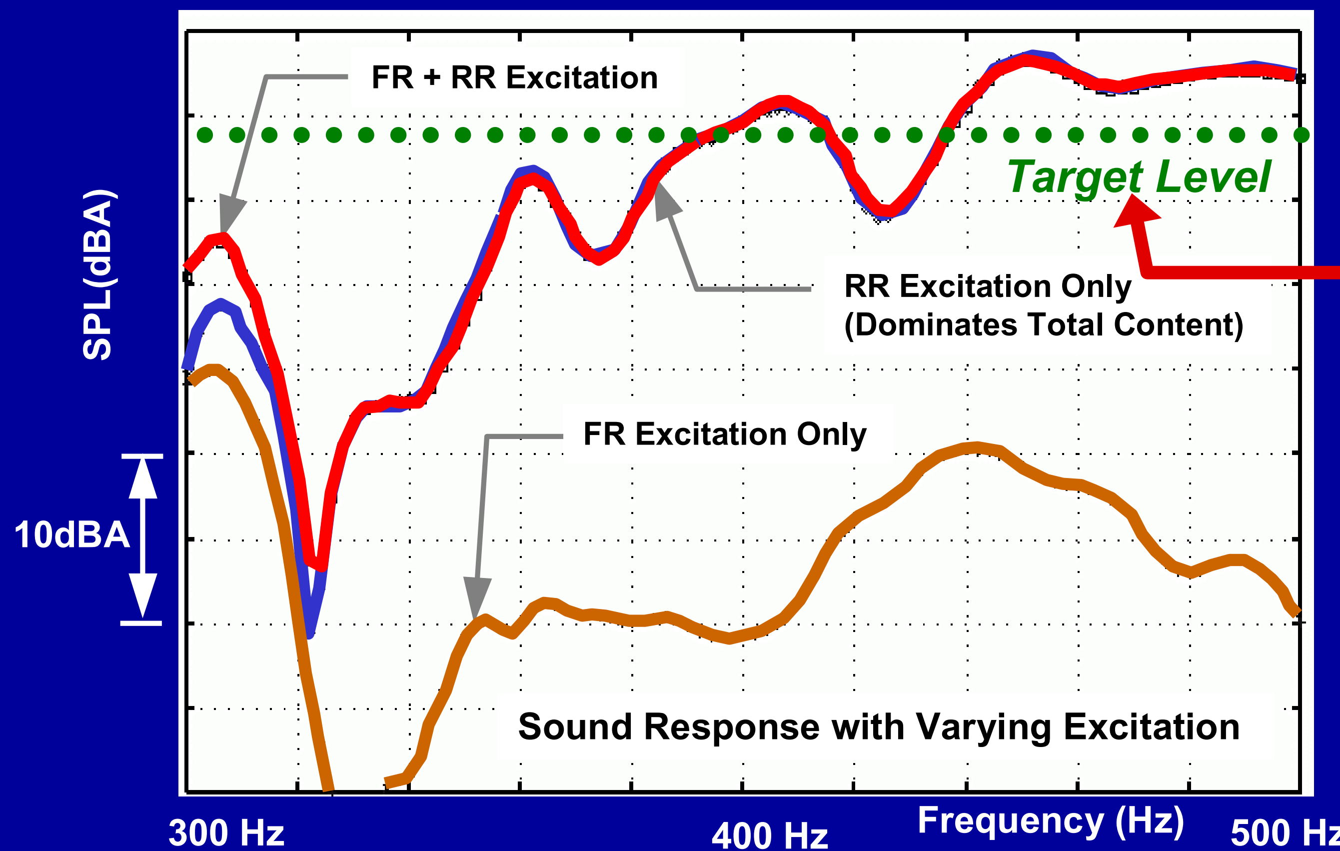
Reference Baseline Confidence Criterion
For Operating Response Simulations



Confidence Criterion: Simulation result must fall within the band of test variation.

Axle Whine Example

- Design work was focused in the beginning towards achieving generic targets for all noise paths
- As the design was firmed out, full vehicle analysis revealed under target performance for Driver's ear SPL response which was dominated by rear excitation



Must define Targets for the Simulation to know when goal is reached!!!

[Figure Courtesy of DaimlerChrysler Corporation]

Conclusions:

Significant Product Variation exists even in best-in-class vehicles.

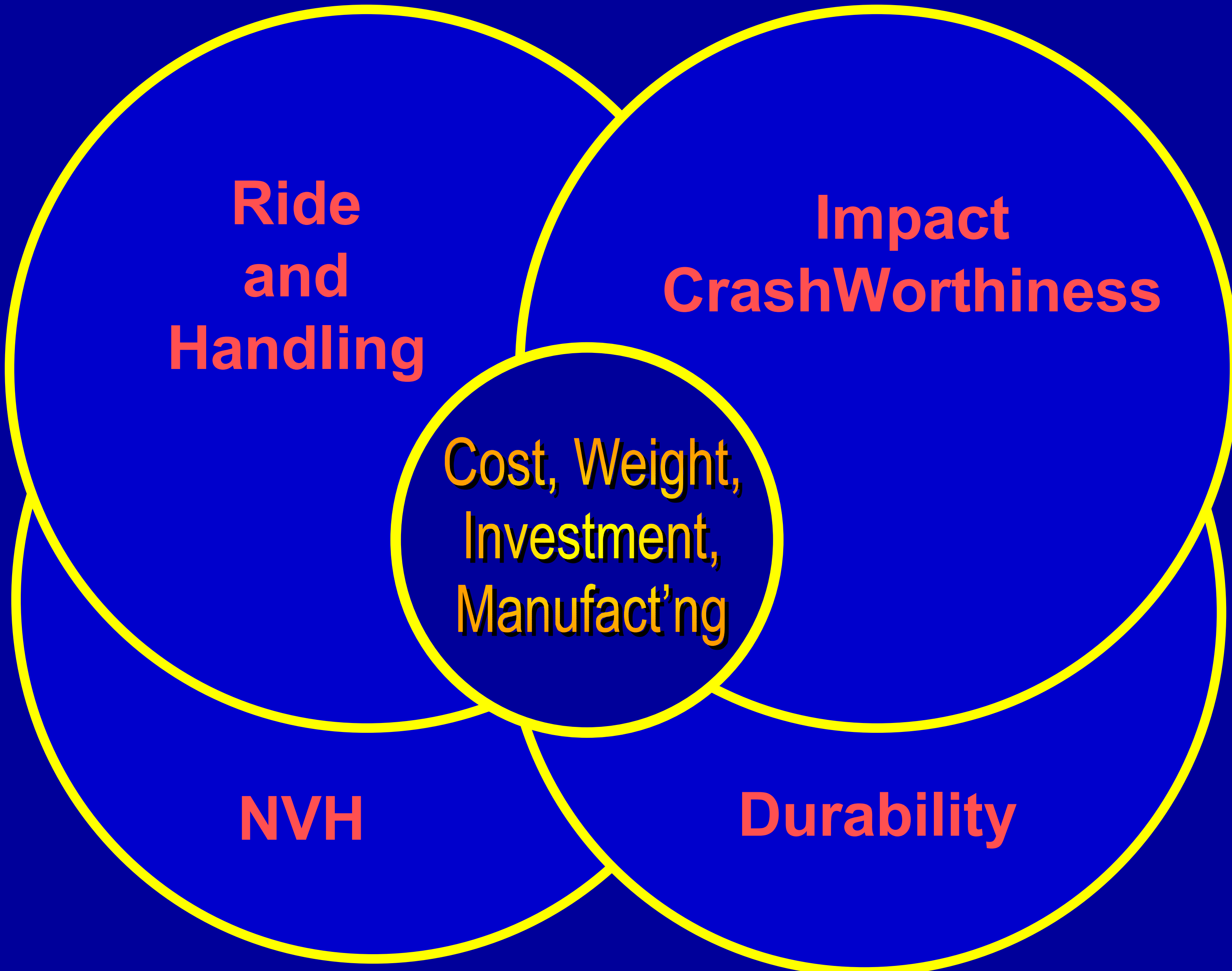
Correlation should be considered as being within the band of variability whether test or simulation.

The Confidence Criteria, for operating responses, is a relatively challenging condition to meet when considering the following:

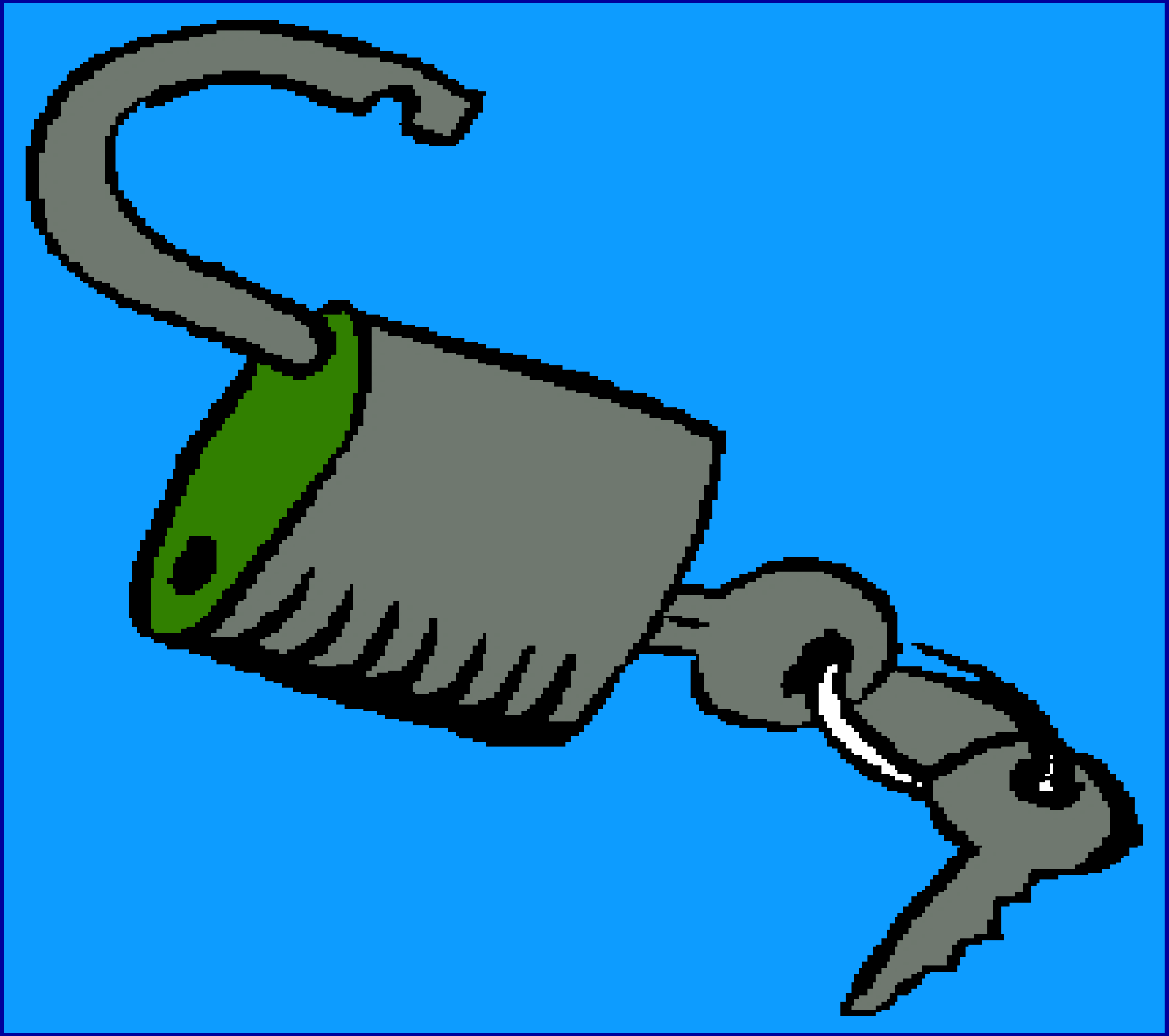
- ✓ It uses the same bandwidth as Kompella (Ref. 8), determined from simple FRF's, while the criteria is for operating responses which are subject to additional variation in the operating loads.
- ✓ It assumes that one test will generate the mean response level in the band subject to the condition that a "qualified" median performer will be tested. This requires a test engineer extremely experienced with the vehicle line in order to "qualify" the vehicle.

Best hope for reduced product development times is a coordinated effort of Virtual Vehicle Simulation and Reference Baseline and Physical Prototype Testing to grasp the complexities of NVH responses and the robustness of their sensitivity to variation.

Competing Vehicle Design Disciplines



The Fundamental Secret of Structure Borne NVH Performance



Revealed here tonight !

Fundamental Secret to Making Money in the Stock Market

Buy Low and Sell High !

The Fundamental Secret of Structure Borne NVH Performance

To Minimize Structure Borne NVH response, always connect Sub-systems at locations where motion is at a Minimum.

Meets Conditions of the Attenuations Strategies

- *Minimize the Source Load*
- *Manage Mode Placement*
- *Provide Isolation*
- *Mount at Nodal Points*
- *Provide Dynamic Absorber*
- *Reduce Source - Receiver Mobility*

The Fundamental Secret of Structure Borne NVH Performance

To Minimize Structure Borne NVH response, always connect Sub-systems at locations where motion is at a Minimum.

That's All Folks !

Thank You for Attending the

SAE Structure Borne NVH Workshop

Your Presenters tonight were:

Alan Duncan, Automotive Analytics, Inc.

Greg Goetchius, Material Sciences Corp.

Sachin Gogate, Altair Engineering, Inc.

Visit: www.AutoAnalytics.com/papers.html
to download the Structure Borne NVH Workshop (May 12)