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Experimental Investigation of Vehicle Occupancy Effects on Secondary Path Characteristics and ANC Performance

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Abstract

In automotive active road noise control (ARNC) systems, the secondary path between a control loudspeaker and an error microphone plays a critical role in determining control performance. Although passenger occupancy changes frequently during vehicle operation, its influence on secondary-path characteristics and ARNC performance has not been thoroughly investigated.

This paper experimentally investigates occupancy-induced secondary-path variations in a production passenger vehicle. Secondary paths were measured under occupied and unoccupied passenger-seat conditions using headrest speakers and door-mounted woofers. Variations in amplitude response, spectral shape, phase characteristics, and group-delay behavior were evaluated using correlation coefficients and average absolute differences.

The results show that passenger occupancy produces measurable secondary-path variations throughout the cabin. Headrest-speaker paths exhibited predominantly local changes near the occupied seat, whereas door-speaker paths showed variations across multiple microphone locations, indicating cabin-wide acoustic effects. Passenger-side microphones generally exhibited larger variations than driver-side microphones, although measurable changes were also observed at remote locations.

Occupancy was found to affect not only path amplitude but also spectral shape, phase characteristics, and group-delay behavior. However, the frequency regions exhibiting the largest secondary-path variations did not necessarily coincide with those showing the largest ARNC performance degradation. Instead, secondary-path mismatch caused a broadband reduction in ARNC attenuation.

These findings demonstrate that passenger occupancy modifies both local and global acoustic transmission characteristics inside the cabin and provide practical guidance for occupancy-aware secondary-path compensation strategies in automotive ARNC systems.

Keywords: *Secondary Path, Active Noise Control, Vehicle Occupancy Effect*

1. Introduction

Road noise is one of the dominant factors affecting ride comfort in modern passenger vehicles, particularly in the low-frequency region where passive noise treatments become less effective. Active Road Noise Control (ARNC) systems reduce low-frequency road noise by generating anti-noise signals through vehicle loudspeakers and minimizing residual noise measured at error microphones. [1][3]

The performance of an ARNC system strongly depends on the accuracy of the secondary-path model, which represents the acoustic transfer function between a control loudspeaker and an error microphone. Since adaptive control algorithms utilize an identified secondary-path model, mismatch between the modeled and actual secondary paths may degrade control performance. [2][4]

In practical vehicle environments, passenger occupancy continuously changes the acoustic boundary conditions inside the cabin and may modify acoustic propagation paths between loudspeakers and microphones. However, it remains unclear whether occupancy-induced secondary-path variation is limited to the occupied seating position or affects acoustic transmission characteristics throughout the cabin.

This paper investigates the influence of passenger occupancy on secondary-path characteristics and ARNC performance in a production passenger vehicle. Secondary paths were measured under occupied and unoccupied passenger-seat conditions using headrest speakers and door-mounted woofers, and their effects on ARNC performance were evaluated under

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occupancy-induced secondary-path mismatch conditions.

2. Experimental Setup

2.1 Vehicle and ARNC Configuration

Experiments were conducted in a production passenger vehicle equipped with an active road noise control (ARNC) system. The experimental setup consisted of four error microphones, four headrest speakers, and four door woofers.

The four error microphones were installed at the driver-side outer, driver-side inner, passenger-side inner, and passenger-side outer headrest positions. All microphones were digital microphones integrated into the corresponding headrests. Throughout this paper, these microphone locations are denoted according to the naming convention summarized in Table 1.

Drv Outer	Drv Inner	Psg Inner	Psg Outer
FLL	FLR	FRL	FRR

Table 1. Naming Convention for Error Microphone Positions

The control loudspeaker system consisted of four headrest speakers and four door woofers. The headrest speakers were integrated into the corresponding driver-side outer, driver-side inner, passenger-side inner, and passenger-side outer headrest positions. In addition, four door woofers were installed in the vehicle doors, with one woofer located in each door.

2.2 Occupancy Condition

To investigate the influence of passenger occupancy on secondary-path characteristics, measurements were conducted under both occupied and unoccupied passenger-seat conditions. In the occupied condition, a passenger was seated in the front passenger seat during the measurement, whereas the seat remained empty in the unoccupied condition.

Except for passenger occupancy, all experimental conditions, including microphone locations, loudspeaker configuration, vehicle condition, and measurement procedures, were kept unchanged.

To evaluate measurement repeatability, secondary-path measurements were conducted repeatedly under each occupancy condition. The repeated measurements were subsequently averaged to obtain representative secondary-path responses for the occupied and unoccupied conditions.

2.3 Secondary Path Measurement

The secondary path was defined as the transfer function between a control loudspeaker and an error microphone.

Secondary-path measurements were conducted using a swept-sine excitation signal. For each loudspeaker–microphone combination, the secondary-path response was calculated from the measured loudspeaker output and the corresponding microphone input signal.

Measurements were performed for all loudspeaker–microphone combinations, including the four headrest speaker-to-error microphone paths and the door-woofer-to-error microphone paths. In the headrest-speaker configuration, each speaker was paired with its corresponding target-position error microphone. For the door-woofer configuration, each door woofer was evaluated with all four error microphones.

For each loudspeaker–microphone pair, frequency responses were obtained under both occupied and unoccupied passenger-seat conditions. The measured responses were subsequently analyzed in terms of amplitude response, spectral-shape similarity, phase response, and group-delay characteristics.

Correlation coefficients were used to quantify changes in spectral shape, while the Average Absolute Difference (AAD) was used to quantify occupancy-induced amplitude variations.

Correlation Coefficient :

$$\rho = \frac{\sum_{k=1}^{N}(X_k - \bar{X})(Y_k - \bar{Y})}{\sqrt{\sum_{k=1}^{N}(X_k - \bar{X})^2}\sqrt{\sum_{k=1}^{N}(Y_k - \bar{Y})^2}}$$

AAD :

$$AAD = \frac{1}{N}\sum_{k=1}^{N}\left|A_{Occupied}(k) - A_{NonOccupied}(k)\right|$$

Where $A_{Occupied}(k)$ and $A_{NonOccupied}(k)$ denote the secondary-path amplitudes at frequency bin kkk under the occupied and unoccupied conditions, respectively.

2.4 ARNC Performance Evaluation

To evaluate the influence of occupancy-induced secondary-path variation on ARNC performance, a secondary-path mismatch experiment was conducted. All performance measurements were performed with a passenger seated in the front passenger seat. Two secondary-path models were evaluated. In the matched condition (Performance-Passenger SP), the ARNC system utilized a secondary-path model measured under the occupied condition. In the mismatched condition (Performance-NoPassenger SP), the ARNC system utilized a secondary-path model measured under the unoccupied condition while the passenger remained seated during performance evaluation.

As a result, the physical cabin condition was identical for both cases, and only the secondary-path model used by the controller differed. This approach enabled the isolated evaluation of ARNC performance degradation caused by occupancy-induced secondary-path mismatch.

2.5 Performance Metrics

Noise attenuation was evaluated using A-weighted sound-pressure-level measurements.

For each error microphone, attenuation was calculated as

$$Attenuation = Noise_{off} - Noise_{on}$$

where

$Noise_{off}$ is the noise level with ARNC disabled

$Noise_{on}$ is the noise level with ARNC enabled

Performance degradation caused by secondary-path mismatch was evaluated by comparing the attenuation

obtained using the matched and mismatched secondary-path models.
To investigate frequency-dependent performance changes, attenuation results were analyzed in multiple frequency bands corresponding to the primary control bandwidth of the ARNC system.

3. Secondary Path Variation Analysis

3.1 Headrest Speaker Paths

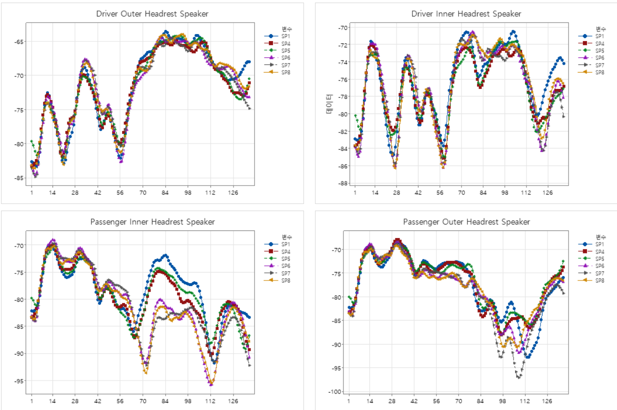

Figure 1. Headrest speaker-Error SP Amplitude Spectrums

	SP-Passenger			
	FLL	FLR	FRL	FRR
SP-NoPassenger	0.979	0.941	0.771	0.937

Table 2. Headrest speaker-Error Average Correlation Coefficients

Figure 1 presents representative secondary-path amplitude responses measured from the headrest speakers to the corresponding error microphones under occupied and unoccupied passenger-seat conditions. Because the headrest speaker and error microphone are positioned in close proximity and are primarily associated with a single seating position, occupancy-induced variations were expected to be localized around the occupied seat.
The experimental results generally supported this expectation. Driver-side microphones (FLL and FLR) maintained relatively high cross-condition correlation coefficients and exhibited only small amplitude variations. In contrast, the passenger-side microphones showed larger occupancy-induced changes.
However, the measured variations were not uniform even within the passenger-side region. The average cross-condition correlation coefficient at FRL was approximately 0.771, whereas FRR maintained a considerably higher value of approximately 0.937. This observation indicates that the occupancy effect cannot be explained solely by microphone proximity to the passenger.

	FLL	FLR	FRL	FRR
Avg Abs Diff	0.84174	1.15938	3.44502	1.86878

Table 3 Headrest speaker–Error Average Absolute Differences

The average absolute difference analysis further supports this observation. As summarized in Table 3, FRL exhibited the largest amplitude variation among all microphone locations. Although FRR maintained a relatively high correlation coefficient, its average absolute difference remained larger than those observed at the driver-side microphones. This indicates that the occupancy-induced variation mechanisms differed between the two passenger-side microphones.
Specifically, FRL exhibited both spectral-shape and amplitude variations, whereas FRR showed primarily amplitude-related changes while maintaining relatively similar spectral characteristics. These findings suggest that occupancy-induced secondary-path variation is influenced not only by seating position but also by the dominant acoustic propagation and reflection paths associated with individual speaker–microphone combinations.

3.2 Door Speaker Paths

Unlike the headrest-speaker configuration, each door woofer is acoustically coupled to multiple error microphones through longer propagation paths involving both direct and reflected sound components. Consequently, occupancy-induced acoustic changes are expected to affect a broader range of speaker–microphone combinations.

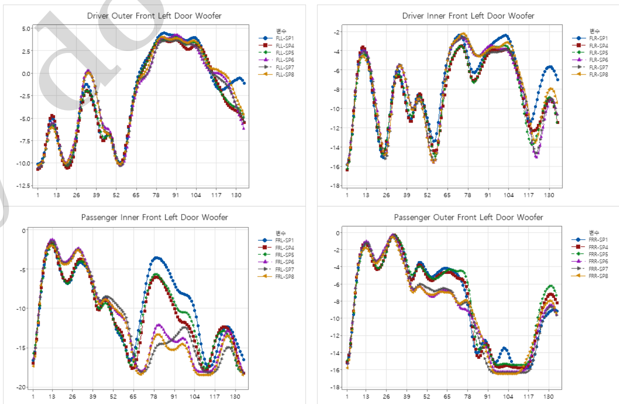

Figure 2. FRT Left Door Woofer-Error SP Amplitude Spectrums

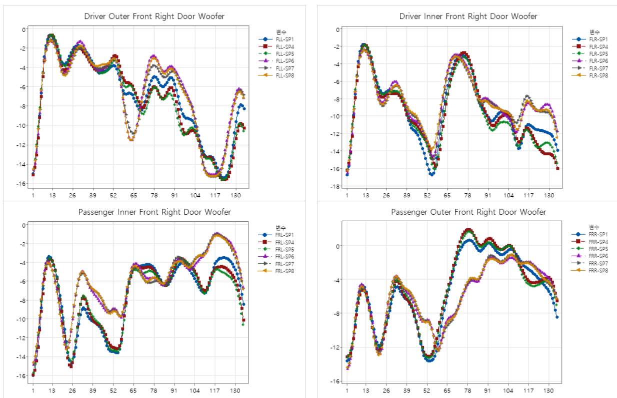

Figure 3. FRT Right Door Woofer-Error SP Amplitude Spectrums

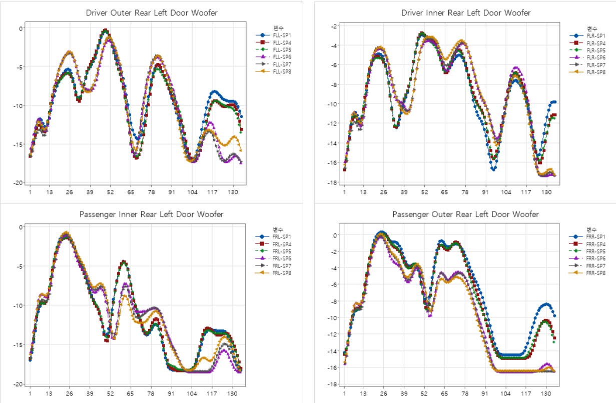

Figure 4. RR Left Door Woofer-Error SP Amplitude Spectrums

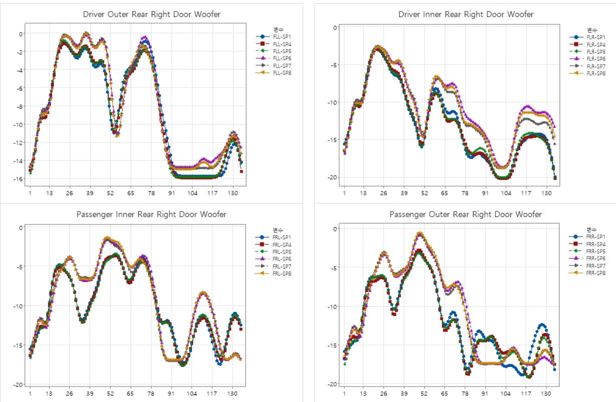

Figure 5. RR Right Door Woofer-Error SP Amplitude Spectrums

Figure 2-5 shows each secondary-path amplitude responses measured for the door-speaker paths under occupied and unoccupied conditions. Compared with the headrest-speaker paths, occupancy-induced variations were observed over a wider range of microphone locations, indicating that the influence of passenger occupancy is not confined to the immediate vicinity of the occupied seat.

		Microphone			
		FLL	FLR	FRL	FRR
Speaker	Front Left	0.981	0.954	0.756	0.970
	Front Right	0.883	0.932	0.836	0.809
	Rear Left	0.849	0.883	0.889	0.946
	Rear Right	0.982	0.963	0.872	0.891

Table 4. Door speaker-Error Average Correlation Coefficients between

Speaker	Microphone				
	FLL	FLR	FRL	FRR	SUM
HeadRest	0.842	1.159	3.445	1.869	7.315
Front Left	0.697	0.952	2.815	1.205	5.669
Front Right	1.562	1.476	1.951	1.968	6.957
Rear Left	1.955	1.379	1.840	2.308	7.483
Rear Right	1.051	2.101	2.159	2.374	7.684
SUM	6.106	7.068	12.210	9.724	

Table 5. Door speaker–Error Average Absolute Differences

To quantify these variations, average cross-condition correlation coefficients and average absolute differences were calculated for each speaker–microphone combination. The results are summarized in Table 4 - 5.

In general, passenger-side microphones exhibited larger occupancy-induced variations than driver-side microphones. When the average absolute differences were accumulated across all door-speaker paths, the largest variation was observed at Psg Inner (FRL, 12.210 dB), followed by Psg Outer (FRR, 9.724 dB), Drv Outer (FLL, 7.068 dB), and Drv Inner (FLR, 6.106 dB). These results indicate that occupancy-induced path variations are more pronounced on the passenger side of the cabin.

Correlation analysis revealed that occupancy-induced variations were not uniformly distributed even among microphones located near the passenger seat. The Passenger Inner microphone consistently exhibited the lowest correlation coefficients across most door-speaker configurations. For example, the front-left door woofer showed a correlation coefficient of 0.756 at Passenger Inner, whereas the adjacent Passenger Outer microphone maintained a considerably higher value of 0.970. These results suggest that the observed SP correlation, and thus the degree of path variation, cannot be fully attributed to the geometric proximity to the occupancy change location alone.

Average absolute difference analysis provided a complementary observation. While Passenger Inner exhibited both low correlation coefficients and large amplitude variations, Passenger Outer maintained relatively high correlation values despite noticeable amplitude differences. This suggests that occupancy-induced variations at Passenger Outer were mainly associated with amplitude changes, whereas Passenger Inner experienced both spectral-shape and amplitude modifications.

In addition, measurable variations were observed not only at passenger-side microphones but also at driver-side microphones. Although the accumulated variations at Driver Outer and Driver Inner were smaller than those at Passenger Inner and Passenger Outer, they were not negligible. Furthermore, each door woofer exhibited a different variation pattern across microphone locations. These results indicate that occupancy-induced SP variation is influenced by the dominant acoustic propagation and reflection paths associated with individual speaker–microphone combinations, rather than by passenger proximity alone.

Therefore, passenger occupancy should not be regarded as a purely local disturbance. Instead, occupancy modifies acoustic transmission characteristics throughout the cabin, while the magnitude and type of variation depend on the underlying speaker–microphone path.

3.3 Phase and Group Delay Characteristics

Additional analyses were performed using phase responses and group-delay characteristics.

The measured results showed that passenger occupancy could alter phase-transition frequencies and shift the locations of group-delay peaks for several speaker–microphone paths. These changes indicate that occupancy modifies not only path magnitude but also the acoustic propagation characteristics of the cabin.
However, compared with the amplitude and correlation analyses described previously, the observed phase and group-delay variations were relatively modest. More importantly, the frequency regions where phase-transition shifts and group-delay peak variations occurred did not consistently correspond to the frequency regions where ARNC performance degradation was later observed.
Therefore, although passenger occupancy was found to influence phase and group-delay characteristics, these parameters alone were not sufficient to explain the measured performance degradation. Amplitude variation and spectral-shape variation provided clearer indicators of occupancy-induced secondary-path changes and will therefore be used as the primary descriptors in the subsequent performance analysis.

4. ARNC Performance Evaluation

To evaluate the impact of occupancy-induced secondary-path variation on ARNC performance, attenuation measurements were conducted using matched and mismatched secondary-path models. The matched condition (Performance-Passenger) utilized secondary paths measured under occupied conditions, whereas the mismatched condition (Performance-No Passenger) utilized secondary paths measured under unoccupied conditions while maintaining the same passenger occupancy condition during performance evaluation. Therefore, the measured attenuation difference reflects the influence of occupancy-induced secondary-path mismatch.

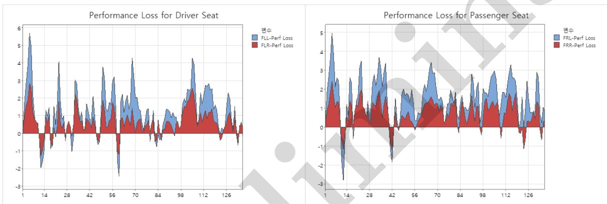

Figure 6. Performance Loss between two Secondary Paths

Figure 6 compares the performance loss observed at the driver-side and passenger-side microphones. Performance loss was calculated as the attenuation difference between the matched and mismatched secondary-path conditions. The results show that occupancy-induced secondary-path mismatch caused attenuation degradation at both driver-side and passenger-side microphones.

In general, larger performance degradation was observed at the passenger-side microphones than at the driver-side microphones. This tendency is consistent with the secondary-path analyses presented in Section 3, where the passenger-side microphones exhibited larger average absolute differences and lower cross-condition correlation coefficients. Therefore, the larger attenuation loss observed at the passenger side can be regarded as a consequence of the larger occupancy-induced secondary-path variation occurring in those paths. [4][5][6]

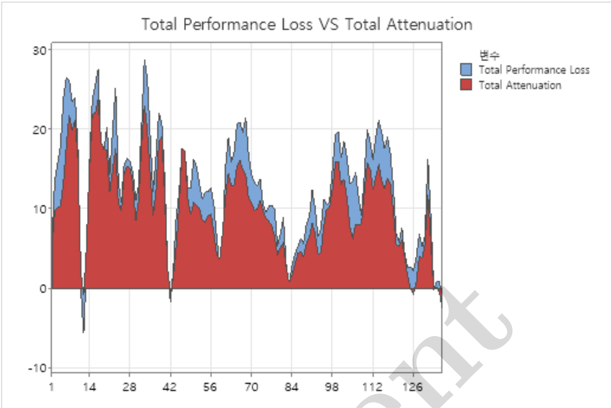

Figure 7. Total Performance Loss VS Total Attenuation

To further investigate the relationship between attenuation loss and ARNC effectiveness at Figure 7, the total performance loss was compared with the total attenuation obtained under the matched condition. The total attenuation represents the maximum achievable ARNC performance when the actual cabin occupancy condition and the secondary-path model are consistent.
As shown in Figure 7, the overall trend of the total performance loss generally follows that of the total attenuation. Larger attenuation losses are observed in frequency regions where ARNC originally provides higher noise reduction, while relatively small losses occur in regions where the baseline attenuation is limited. This tendency is more evident than the relationship between performance loss and individual secondary-path variation metrics.
Interestingly, the frequency regions exhibiting the largest secondary-path variations did not necessarily coincide with those exhibiting the largest attenuation degradation. Similar observations were obtained from the amplitude-response, phase-response, and group-delay analyses presented in Section 3. Although occupancy-induced changes were identified in all of these secondary-path characteristics, the frequencies at which these changes occurred were not consistently aligned with the frequencies exhibiting the largest performance loss.
These results indicate that occupancy-induced secondary-path mismatch influences ARNC performance from a system-level perspective rather than through isolated frequency-specific path variations. Consequently, the magnitude of performance degradation appears to depend not only on the amount of secondary-path variation but also on the control effectiveness of the ARNC system within the corresponding frequency region.

Position	Frequency Range			
	20-500	20-70	70-180	230-330
FLL	0.65	0.72	0.62	0.38

FLR	0.61	1.05	0.50	0.69
FRL	0.72	1.00	0.57	0.64
FRR	0.96	0.98	0.97	0.81
Overall	0.74	0.93	0.66	0.63

Table 6. Band-wise RMS Performance Loss

To quantitatively evaluate the trends observed in Figure 6, the band-wise RMS performance loss was calculated, and the results are summarized in Table 3. The largest degradation was observed within the primary ARNC control bands (20–70 Hz and 70–180 Hz), whereas considerably smaller degradation was found at higher-frequency bands. In addition, the passenger-side microphones generally exhibited greater performance loss than the driver-side microphones. This tendency is consistent with the secondary-path analysis presented in Section 3, where larger average absolute differences and lower cross-condition correlation coefficients were observed for the passenger-side paths.

5. Conclusion

Passenger occupancy introduced measurable changes in secondary-path characteristics, including amplitude response, spectral shape, phase behavior, and group-delay characteristics. For headrest-speaker paths, the largest variations were observed near the occupied seating position, indicating a predominantly local acoustic effect. In contrast, door-speaker paths exhibited variations across multiple microphone locations, demonstrating that occupancy modifies acoustic transmission characteristics beyond the occupied seat region.

ARNC performance evaluation showed that occupancy-induced secondary-path mismatch reduced attenuation at both driver-side and passenger-side microphones. The performance degradation was generally larger on the passenger side, which is consistent with the larger secondary-path variations observed in the corresponding paths. Although noticeable changes were identified in amplitude, spectral shape, phase response, and group delay, the frequency regions exhibiting the largest secondary-path variations did not necessarily coincide with those showing the largest attenuation loss.

From a practical perspective, the required compensation strategy depends on the acoustic path configuration. Headrest-speaker paths were primarily affected around the occupied seating position, suggesting that local path compensation may be sufficient. In contrast, door-speaker paths exhibited occupancy-induced variations across multiple microphone locations, indicating that broader cabin-wide secondary-path compensation may be required when long-distance loudspeaker–microphone paths are employed in automotive ARNC systems.

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