

Influence of Urban Road Characteristics on Traffic Noise

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Abstract: Urban road networks significantly influence traffic noise. However, existing studies have neglected the causal chain between road characteristics and traffic noise; thus, clarity on their influencing mechanisms is lacking. In this study, structural equation models were developed to explore the mediated effect of road characteristics on traffic noise through traffic flow using data from field measurement in Dalian City, China; paired comparisons of scenarios through microscopic and macroscopic traffic simulations were performed for further analysis. The results show that lane number influences traffic noise mainly in terms of the number of vehicles in a group (NVG). More lanes indicate increased traffic demand due to connected urban land, which increases the NVG and, in turn, increases noise intensity but decreases noise amplitude. The influence of road segment length (RSL) on traffic noise mainly depends on the suppression effect. A longer RSL allows for higher vehicle speeds, leading to increased noise intensity and reduced noise amplitude. This also indicates that traffic flows disperse more easily, decreasing the NVG and, in turn, reducing noise intensity and increasing noise amplitude. Road junctions (RJ), which are classified according to the presence or absence of traffic lights, have significant direct effects on both noise intensity and noise amplitude, which are both likely to increase as drivers accelerate or decelerate in the middle of the road segment. These findings provide a reference for local governments and urban planners when working to improve quality of life in urban areas.

Keywords: traffic noise; road characteristics; road network; traffic flow; mediated effect; structural equation modelling

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1. Introduction

Noise pollution has a detrimental impact on quality of life. It diminishes comfort levels, inhibits the ability to communicate, disturbs tranquillity, and can even cause psychological problems and cardio-cerebrovascular diseases (Halonen et al., 2015; Stansfeld et al., 2005; Van Kempen et al., 2012). Of all the environmental stressors that can affect lives, noise pollution is ranked second (EEA, 2014; Fritschi et al., 2011; Ouis, 2001). Traffic noise is the primary source of noise pollution (SCU, 2017). One-third of the roads in China's metropolitan areas exceed the national standard permissible limit of 70 dB(A) (MEP, 2018). The effects of noise pollution at night are even more extreme (MEP, 2017).

Numerous factors affect traffic noise, among which traffic flow is an important influencing factor. The road network determines the distribution of traffic flow in an urban space and affects driver behaviour (Williams et al., 2014; Wu et al., 2008), which further affects noise levels. Thus, municipal-scale urban road networks, as well as block-scale road characteristics, are the central focus of urban traffic noise management (D'Alessandro et al., 2014; Naish, 2010; Ruiz-Padillo et al., 2014).

A number of studies have made progress in terms of understanding the influence of urban road networks on traffic noise. Wang and Kang (2011) studied noise pollution patterns in Wuhan, China, and Manchester, U.K., and stated that road coverage is significantly related to traffic noise. They also found different trends in the two cities in terms of the correlations between urban morphological indices and noise levels. Salomons and Pont (2012) reported that the spatial distribution of traffic noise is a function of local vehicle kilometres, population density, and urban form, concluding that road network density correlates positively with traffic noise. Ryu et al. (2017) found a positive relationship between road area density and traffic noise through spatial correlation analysis of noise mapping. Their conclusions contradicted those of Salomons and Pont (2012) with respect to the impact that the floor space index has on traffic noise. Tang and Wang (2007) and Sheng and Tang (2011) compared different arrangements of road networks in Macau, demonstrating that narrow roads, complex road networks, and high-density intersections can lead to higher noise pollution. Barrigón Morillas et al. (2005) and Rey Gozalo et al. (2013) reported that urban noise can be stratified according to road functionality as a communication path between different regions of a city and between adjacent cities. These studies concentrated on the municipal scale, achieving a deep understanding of road networks, which can provide useful guidance to improve traffic noise. However, certain findings still require further clarification.

Additionally, urban planning requires discussion related to road characteristics at the block scale to guide specific design strategies. Certain road characteristics that directly affect the rolling noise of a vehicle, such as road gradient and road pavement, have been

incorporated into various noise prediction models, such as CoRTN, ASJ RTN, and RLS 90 (Garg and Maji, 2014). These road characteristics were not considered in this study as their relationship with traffic noise, as well as their mechanisms, are relatively well known.

Road characteristics that reflect road dimensions, such as road width and road segment length, are closely related to and can effectively predict traffic noise (Golmohammadi et al., 2009). Nevertheless, these ignored discussing with road junctions together, which have been shown to significantly affect traffic noise. Some studies have focused on the noise generated at road junctions and presented detailed findings on intersections (Estévez-Mauriz and Forssén, 2018; Gardziejczyk and Motylewicz, 2016; Li et al., 2017), while ignoring their impact on the noise of an entire road. Therefore, in this study, road characteristics were limited to road width, road segment length, and road junctions to better conform to urban planning needs.

Overall, most previous results only reflect the direct relationship between urban road networks, road characteristics, and traffic noise; however, few previous studies have systematically investigated the intrinsic mechanisms between them. It should also be noted that different vehicle combinations produce different traffic noise levels. Therefore, even on the same road, traffic noise varies depending on the vehicles being driven. Thus, to fully explore the relationship between road networks or roads and traffic noise and, hence, explain contradicting prior conclusions and obtain broader applicable findings, the role of traffic flow should be considered.

The aim of this study is to explore how road characteristics influence traffic noise through traffic flow and to provide a reference for urban planning. First, field measurements were conducted to obtain data in Dalian City, China, for three variables: road characteristics, traffic flow, and traffic noise. Multiple mediation analyses were then performed using structural equation modelling (SEM), with road characteristic data as independent variables, traffic noise data as dependent variables, and traffic flow data as the mediators. The direct effects (DEs) and total indirect effects (TIEs) of road characteristics on traffic noise, as well as specific indirect effects (SIEs), were evaluated. TIEs clarify to what extent road characteristics influence traffic noise through traffic flow, whereas SIEs clarify how road characteristics influence traffic noise through traffic flow. Pathways with a greater effect were further investigated through microscopic traffic and noise simulations.

2. Methods

2.1. Definitions of vehicle groups

For conventional measurements of traffic noise (ISO, 2017), it is important to continue the measurement over a sufficiently long period. However, in urban agglomerations, traffic

rarely flows freely (Iannone et al., 2013). Stop-start conditions imposed by traffic lights and intersections can cause pauses in traffic flow. Therefore, acquired traffic noise data do not have a clear corresponding relationship with real-time traffic flow (Muaz et al., 2017). This study uses vehicle groups as the research object to ensure that traffic noise data are mainly attributable to passing vehicles as vehicle grouping is very common, especially when the traffic volume is large (but not saturated).

Vehicle groups were identified by applying the following criteria: 1) the average number of vehicles per lane in the group is greater than one; 2) the vehicles in a group are in 'car-following' status, meaning that the headway time is less than 5 s (Parker 1996; Puan et al., 2004); that is, the headway distance in the group did not exceed 40 m given an average speed of 30 km/h; and 3) the distance between vehicle groups is not less than 100 m to increase the attenuation of noise from adjacent groups.

2.2. Road characteristics data acquisition

As depicted in Fig. 1, three indicators were selected as road characteristic variables: lane number (LN), road segment length (RSL), and road junction (RJ). LN represents the road width based on the number of lanes, which is considered a more representative parameter than the actual width of the road. The RSL is the distance between two adjacent motor vehicle intersections. The RJ is classified according to the presence or absence of traffic lights in the direction of the vehicle's travel. Roundabouts, another type of road junction, are not discussed in this study owing to the difficulties in collecting a sufficient number of measured samples to meet the requirements of both one-way roads and those ending with a roundabout in Dalian, yielding unconvincing results.

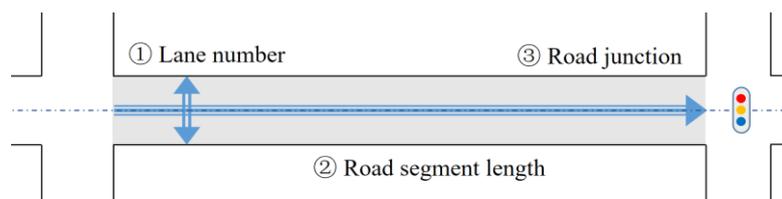


Fig. 1. Illustration of the three road characteristic indicators.

To clearly separate vehicle groups and reduce noise interference, only segments from one-way roads were included in the sample. This study selected samples in Dalian City, north-eastern China. Dalian's central road network was created during the colonial period under Russian and Japanese rule, with dense one-way roads that range from two to six lanes, which is rare in other Chinese cities. These features render Dalian particularly suitable for this study. In total, 20 typical one-way road segments were selected as samples. The roads have a gradient of < 3% and a lane width of approximately 3.5 m. Conclusion biases due to the pavement type were excluded as the pavements of the road segment samples in this study were essentially the same, consisting of conventional medium grain

asphalt concrete. The location distribution in Dalian is shown in Fig. 2; Table 1 presents an overview of the sampled road segments.



Fig. 2. Location distribution of sampled road segments in Dalian, China (source: Google Earth).

2.3. Traffic noise and flow data acquisition

Vehicle movement in the middle of a road segment is relatively stable, whereas at intersections, it is often altered by certain driving behaviours, such as acceleration, deceleration, and lane changing. Therefore, noise measurement points were set in the middle of the road segments to better reflect the influences of road characteristics on traffic noise, as shown in Fig. 3. Noise measurements commenced when the first car of the vehicle group arrived at the measurement point and ceased when the last car arrived at that point.

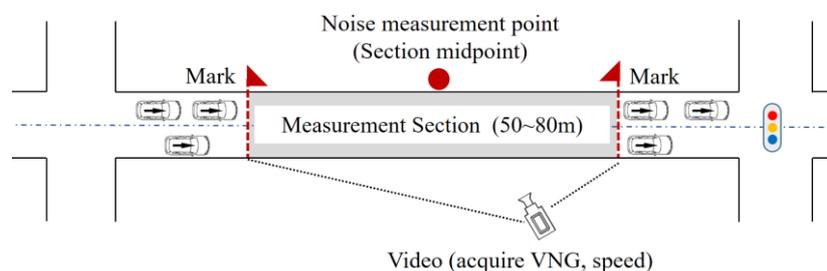


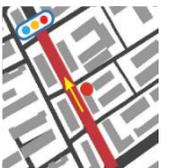
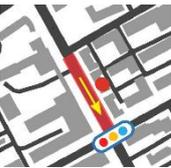
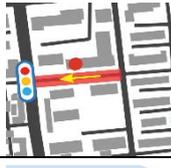
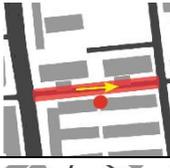
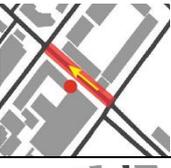
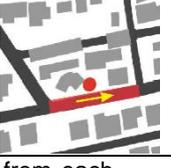
Fig. 3. Illustration of the measurement method.

Traffic noise is mainly measured in terms of two indicators: continuous equivalent A-weighted sound level, L_{Aeq} , and statistical percentage sound level (i.e., L_{10} , L_{50} , and L_{90}). L_{Aeq} is used to represent noise intensity as it has an improved correlation with the subjective perception of sound (Yang and Kang, 2005). The range from L_{10} – L_{90} is used to represent noise amplitude, which is related to noise fluctuation (Can et al., 2008).

The following steps were taken to eliminate noise interference: 1) we ensured that noise from passing vehicles exceeded the background noise by at least 10 dB to avoid measuring other obvious noise sources, such as construction and crowd noise; 2) noise from other sudden sources, such as sirens or people, was excluded; and 3) noise from other vehicles, such as motorcycles and bicycles, was also excluded owing to its low occurrence frequency.

Traffic flow variables consisted of three indicators. The first was the number of vehicles in a group (NVG), which reflects the traffic flow rate. This was used instead of traditional flow rate (vehicles per hour), which unsuitable when attempting to evaluate short-term changes in traffic flow. The second variable was the group speed (km/h). For each vehicle group, three to five typical vehicles were selected, each of which had a status of ‘car-following’ with no lane changes. A segment speed was then obtained using video (Fig. 3), and the average group speed was calculated. The third variable was the heavy vehicle percentage (HVP); that is, the ratio of heavy vehicles (mainly buses and trucks) to total vehicles.

Table 1. Overview of sampled road segments.

Name	No.01 ZS		No.02 FN		No.03 TY		No.04 JX	
LN	6		2		5		2	
RJ ^a	A		A		P		A	
RSL(m)	130		188		160		130	
NS ^b	39		41		40		6	
Name	No.05 FF1		No.06 GRJ1		No.07 BS2		No.08 BS1	
LN	5		5		4		5	
RJ ^a	P		P		P		P	
RSL(m)	135		162		148		116	
NS ^b	36		26		36		24	
Name	No.09 WS1		No.10 FF2		No.11 GRJ2		No.12 WS2	
LN	2		5		5		2	
RJ ^a	P		P		P		P	
RSL(m)	67		132		139		131	
NS ^b	37		31		29		44	
Name	No.13 MZ		No.14 YP		No.15 SC		No.16 YH	
LN	2		2		2		2	
RJ ^a	P		A		P		A	
RSL(m)	143		155		58		100	
NS ^b	45		23		42		40	
Name	No.17 NS1		No.18 NS2		No.19 NS3		No.20 QQ	
LN	3		3		3		2	
RJ ^a	A		P		P		A	
RSL(m)	227		124		94		94	
NS ^b	42		26		41		42	

Note. ^aP: Traffic light presence; A: Traffic light absence; ^bNS: number of datasets obtained from each sampled road segment. Red areas identify selected road segments, which are consecutive vehicle roads, and are determined by two adjacent motor vehicle intersections; the red circle is the measurement position. Image sourced from Baidu Maps. LN, lane number; RJ, road junction; RSL, road segment length.

Noise was measured using a Class 1 B&K 2250 sound level meter equipped with a wind protector. The meter was placed at a height of 1.5 m, at a distance of 1.5 m from the road curb, and at least 5 m from the facades of buildings (Barrigón Morillas et al., 2016). Measurements were collected during non-peak traffic hours; that is, between 1 p.m. and 3

p.m. on non-holidays. Weather conditions were cloudy, dry, and with a light breeze, with smooth traffic flow during the measurements. In total, 742 datasets were obtained; the number of datasets obtained for each sampled road segment are presented in Table 1. The average measurement time for each dataset was 38.8 s (SD = 30).

2.4. Sample independence verification

The Wald-Wolfowitz runs test (Bartels, 1982; Wald and Wolfowitz, 1940) is a statistical test that determines whether the samples of a sequence are mutually independent and applies only to binomial variables. A run is a sequence of identical samples preceded and succeeded by different events or no event. In this study, the string of data obtained at the same measurement point was transformed into binomial data based on certain cut-off points obtained from its median. A string of data with too many or too few runs indicates that such data may not be random. As presented in Table A.1, the majority of the runs were insignificant, indicating that each dataset taken at the same point is independent.

This inference can also be explained empirically. The vehicle groups that passed in sequence were random and there was no mutual restriction between them. The measurements were also discontinuous because passing vehicles were often excluded as a result of not meeting the definition of vehicle grouping. This rendered the samples of traffic flow independent since there was no correlation among the passing vehicles while the corresponding traffic noise was also independent.

2.5. Statistical analysis

SEM is an extension of several multivariate techniques, including multiple regression analysis, pathway model analysis, and factor analysis. SEM is a more powerful alternative to regression analysis because simple regression models can only consider the direct effects that road characteristics have on traffic noise, and thus neglect the indirect effects (Fyhri and Klæboe, 2009; Hong and Jeon, 2015).

Compared with a simple mediation model, a multiple mediation model enables us to test multiple mechanisms from the antecedent to consequent variable (Hayes, 2013). Therefore, this study used the multiple mediation model via the PROCESS macro developed by Hayes (2013) and the IBM SPSS macros, which allow simultaneous testing of the DEs, TIEs, and SIEs. The TIE is the aggregate mediated effect of each SIE involved. Each SIE is associated with one of the road characteristic indicators, one of the traffic flow indicators, and one of the traffic noise indicators. The significance of each effect was tested using nonparametric bootstrapping, which is a computer-based resampling method that has higher statistical capabilities compared with the causal step and Sobel test methods (Hayes, 2009; Holbert and Stephenson, 2003). DEs, TIEs, and SIEs were calculated for 5,000 bootstrap samples as recommended by Preacher and Hayes (2008). Significant

mediation is achieved if the 95% bias-corrected confidence intervals of the indirect effect parameters do not include zero. In addition, each dataset obtained at the same measurement point was directly applied in subsequent analyses since it was regarded as independent.

2.6. Traffic and noise simulations

There are two methods to analyse the results obtained from statistical analysis: (1) microscopic traffic and noise simulation, and (2) macroscopic traffic simulation.

The results can be validated through microscopic traffic and noise simulations based on vehicle driving behaviour. These simulations consist of three sequential parts: microscopic traffic simulation, vehicle noise emission simulation, and sound propagation simulation.

First, microscopic traffic simulation was performed to simulate traffic flow and obtain vehicle status data, including the position, speed, and acceleration of each vehicle at each simulation time step. In this study, Vissim vision 5.2 software was used. It is a time-based simulation in which driver-vehicle-units are modelled as single objects incorporating the Wiedemann 74 car-following model for urban traffic situations (Fellendorf, 2010). Then, status data of the vehicles were used in the vehicle noise emission model to calculate the noise emissions for each vehicle at a specific moment. The single vehicle noise emission model used in this study was obtained by regression analysis of measured data for Chinese roads (Li et al., 2017). Finally, the vehicle position and noise emission were used in the sound propagation model to calculate the individual contribution of each vehicle at the receiver. Thus, the instantaneous sound pressure level at the receiver can be obtained by a summation of the contribution of each vehicle at the corresponding time-step. Distance and noise attenuation due to other factors were fully considered in the sound propagation model. Further details have been reported in Li et al. (2017) and the International Standard ISO 9613 (1996). The vehicle noise emission and sound propagation models were developed using a MATLAB procedure developed in this study.

Field measurements for model validation were conducted at Soft Park Road in Dalian, China. One receiving point was set at the middle of the road segment, as shown in Fig. 4. This point was selected in areas without buildings to reduce the influence of reflection. Traffic noise was measured for 20 min at the receiving point in terms of L_{Aeq} , L_{10} , L_{50} , and L_{90} . A simulated road was established based on the measured geometric dimension data, traffic volume data, and traffic control schemes at real intersections. The results show that simulated values of L_{Aeq} , L_{10} , L_{50} , and L_{90} slightly differ from the measured values, with a maximum absolute error of 2.5 dB, as shown in Table 2, which indicates that the accuracy of the model is acceptable.

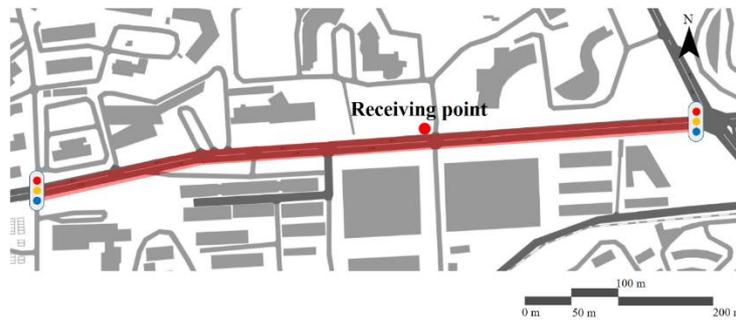


Fig. 4. Sampled road segments for model validation in Dalian, China (source: Baidu Maps).

Table 2. Comparison of simulated and measured L_{Aeq} , L_{10} , L_{50} and L_{90} parameters at the receiving point with a 20-min simulation period.

	L_{Aeq}	L_{10}	L_{50}	L_{90}
Measured data (dB)	70.5	73.2	68.1	61.9
Average of four simulations (dB)	69.8	74.6	67.6	59.4
Difference (dB)	0.7	-1.4	0.5	2.5

The results were also examined through macroscopic traffic simulation. Control delay was chosen as the indicator, which is a criterion for determining the level of service (LOS) at intersections designated by the American Highway Capacity Manual (HCM). It is caused by a control device (i.e., a traffic signal or a STOP-sign), including initial deceleration delay, queue move-up time, stopped delay, and final acceleration delay. The Highway Capacity Software (HCS) vision 7.8 was used to calculate control delays. This software was developed and is maintained by McTrans as a faithful implementation of HCM procedures. This version includes updated modules to implement HCM 6th Edition (TRB, 2016) procedures.

3. Results

Multiple mediation analyses of the 742 datasets were performed using SEM to clarify: 1) the extent to which the road characteristics influence traffic noise and its dependence on changes in traffic flow, 2) the extent to which the effect of each specific pathway is included in the causal chain between road characteristics and traffic noise, and 3) the effect to which differences in road characteristics influence noise intensity and amplitude.

3.1. Correlation analysis

Table 3 lists the means, standard deviations, and correlation matrices for the study variables. The RJ was set depending on the presence of a traffic light at the intersection, i.e., 1 if present and 2 if absent. According to Cohen (1988), there are two pairs of indicators

with strong correlation ($|r| > 0.5$), four pairs with moderate correlation ($0.3 < |r| < 0.5$), 17 pairs with weak correlation ($|r| < 0.3$), and five pairs with insignificant correlation.

Table 3. Means, standard deviations, and correlation matrices for all variables (N = 742).

	Mean	SD	Pearson's r correlations							
			1	2	3	4	5	6	7	8
1. LN	3.38	1.43	1							
2. RSL ^a	131.4	40.4	.260**	1						
3. RJ ^b	1.31	0.46	-.252**	.286**	1					
4. NVG	27.80	34.98	.737**	.148**	-.101**	1				
5. Speed ^c	33.58	9.32	.098**	.331**	.251**	-	1			
6. HVP	0.06	0.09	.176**	-		.138**	.081*	1		
7. LAeq	72.05	3.37	.489**	.221**	-	.554**	.439**	.297**	1	
8. L10-L90	9.05	3.15	-.291**	-.230**	-.179**	-.327**	-.162**	-	-.215**	1

Note. *p < .05; **p < .01 (two-tailed); ^aUnits in meters; ^bTraffic light presence = 1; Traffic light absence = 2; ^cUnits in km/h.

3.2. Structural equation model

Preliminary structural models were established using road characteristic data (LN, RSL, and RJ) as the independent variables, traffic noise data (LAeq and L10-L90) as the dependent variables, and traffic flow data (NVG and group speed) as the mediator variables. LAeq was the dependent variable in Model A while L10-L90 was the dependent variable in Model B, as shown in Fig. 5(a) and 4(b), respectively. HVP was introduced as an independent variable to closely match real scenarios; however, no special analysis was performed. The recommended values of the fit indices were selected according to the guideline reported in Hu and Bentler (1999) and Jackson et al. (2003). Models A and B meet the recommended values for the comparative fit index (CFI), incremental fit index (IFI), Tucker-Lewis index (TLI), goodness-of-fit index (GFI), and adjusted goodness-of-fit index (AGFI), as presented in Table 4. However, models A and B do not meet the recommended values for the chi square to df ratio (χ^2/df ; $6.231 > 2.0$) and root-mean-square error of approximation (RMSEA; $0.084 > 0.05$). This shows that the models have certain defects.

Table 4. Goodness-of-fit of structural equation modelling (SEM). N = 742.

Fit indices		χ^2/df	RMSEA	CFI	IFI	TLI	GFI	AGFI
Recommended value		< 2.00	< 0.05	> 0.90	> 0.90	> 0.90	> 0.90	> 0.90
Model A		6.231	0.084	0.990	0.990	0.929	0.993	0.934
Model B		6.231	0.084	0.986	0.979	0.901	0.999	0.934
Model C		1.698	0.031	0.999	0.999	0.990	0.999	0.982
Model D		1.698	0.031	0.999	0.999	0.987	0.999	0.982

Note. χ^2/df : chi square to df ratio; RMSEA: root-mean-square error of approximation; CFI: comparative fit index; IFI: incremental fit index; TLI: Tucker-Lewis index; GFI: goodness-of-fit index; AGFI: adjusted goodness-of-fit index.

In real scenarios, the NVG may be negatively related to group speed. Therefore, the NVG and group speed were combined to optimise the multiple mediation models, which yielded models C and D, as shown in Fig. 5(c) and 4(d), respectively. L_{Aeq} is the dependent variable in model C, whereas L_{10} – L_{90} is the dependent variable in model D. Table 3 indicates that the fit indices of models C and D were characterised by significant improvement, such that the results for the χ^2/df and RMSEA tests now meet the recommended values, as well as the fact that the other indices improved by varying degrees. Overall, the fit between the theoretical model and measured data is relatively good. Subsequent analysis was performed using models C and D. Interestingly, although the correlation between the group speed and NVG was not strong ($r = 0.081$, $p < 0.05$, see Table 2), the connection between them plays an important role in improving the fitness index. It should be noted that L_{Aeq} represents various indicators of noise intensity, considering the strong correlation between L_{Aeq} and L_{10} , L_{50} , and L_{90} ($r = 0.952$, 0.910 , 0.807 , respectively). This can also be confirmed as follows: if L_{10} , L_{50} , and L_{90} replace L_{Aeq} as the dependent variable in model C (as presented in Table A.2 and Fig. A.1), the fit index values, pathway coefficient, and R^2 of the obtained SEM essentially remain the same.

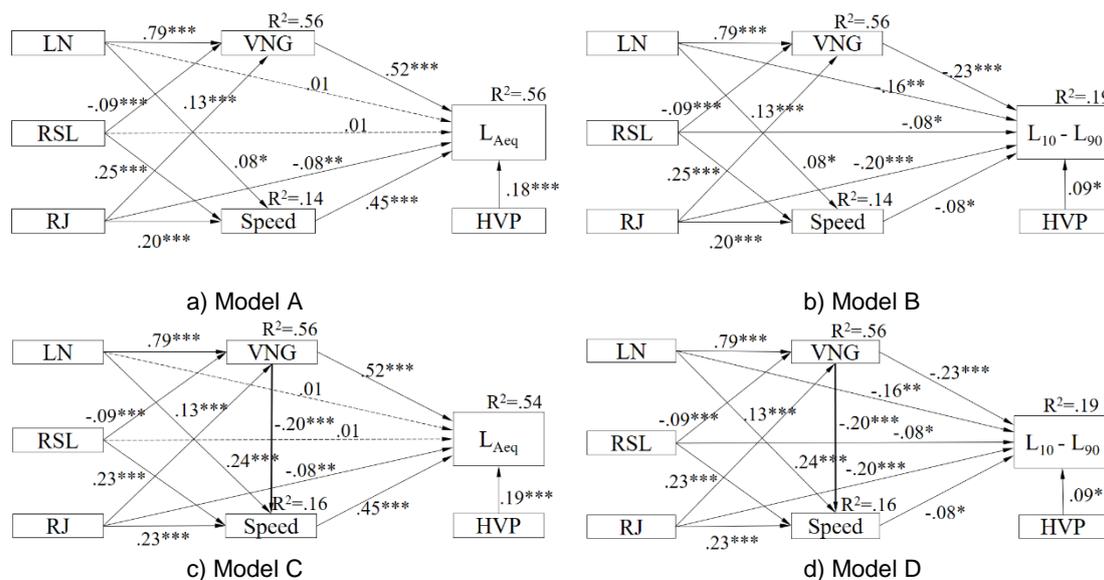


Fig. 5. Structural equation models. (a) Model A: preliminary model with L_{Aeq} as the dependent variable; (b) Model B: preliminary model with L_{10} – L_{90} as the dependent variables; (c) Model C: optimised model with L_{Aeq} as the dependent variable; (d) Model D: optimised model with L_{10} – L_{90} as the dependent variables. *Notes.* LN, lane number; RJ, road junction; RSL, road segment length; HVP, heavy vehicles percentage; NVG, number of vehicles in a group. Numbers in the figure represent standardised regression coefficients derived from the bootstrapping procedure. Solid lines represent the significant indirect pathways (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$)

There are three chained mediated pathways for the SIE of each road characteristic indicator on the noise indicator. Taking LN as an example: 1) SIE1: $LN \rightarrow NVG \rightarrow L_{Aeq}$, 2)

SIE2: LN → Speed → L_{Aeq}, and 3) SIE3: LN → NVG → Speed → L_{Aeq}. According to Preacher and Hayes (2008), SIEs should be examined even when the total effect (TE) is not significant since suppression effects may obscure the SIEs. In this study, all DEs, TIEs, and SIEs were calculated and compared.

3.3. Effect of lane number on noise

Table 5 lists the parameter estimates and confidence intervals of the effect of LN on L_{Aeq}. The TE of LN on noise intensity is positive and significant; when LN increases by 1, L_{Aeq} increases by 1.073 dB (BC 95% CI [0.920, 1.234]). It should be noted that the DE represents the influence that LNs have on noise with respect to the assumption that there are no changes in the NVG and speed. The DE is not significant, which indicates that simple changes in physical space have a minimal effect on noise intensity.

Table 5. Unstandardized direct effect (DE), total indirect effect (TIE), total effect (TE), and specific indirect effect (SIE) of lane number (LN) on L_{Aeq}.

LN → L _{Aeq}	Point Estimate	Product of coefficients		Bootstrap 5,000 times 95% CI					
		SE	Z	Bias corrected			Percentile		
				Lower	Upper	P	Lower	Upper	P
DE & IE & TE									
DE	.025	.111	.225	-.185	.249	.791	-.196	.236	.852
TIE	1.047	.076	13.776	.907	1.201	.000	.906	1.200	.000
TE	1.073	.080	13.413	.920	1.234	.000	.914	1.227	.000
TIE vs. DE	1.022	.173	5.908	.686	1.357	.000	.697	1.363	.000
SIE									
S1. LN → NVG → L_{Aeq}	.961	.065	14.785	.842	1.094	.000	.840	1.093	.000
S2. LN → Speed → L_{Aeq}	.251	.061	4.115	.139	.379	.000	.140	.380	.000
S3. LN → NVG → Speed → L_{Aeq}	-.165	.047	-3.511	-.266	-.080	.000	-.264	-.079	.000
Contrast between SIEs									
S1 vs. S2	.709	.083	8.542	.553	.880	.000	.547	.872	.000
S1 vs. S3	1.126	.090	12.511	.963	1.319	.000	.957	1.310	.000
S2 vs. S3	.416	.098	4.245	.236	.623	.000	.234	.620	.000

Note. DE: direct effect; TIE: total indirect effect; TE: total effect; SIE: specific indirect effect; LN: lane number; NVG: number of vehicles in a group.

Within the TIE, three SIEs are significant with significant differences between them. The greatest effect among these is the pathway via the NVG: when LN increases by 1, the NVG increases by 19.33 vehicles (BC 95% CI [17.79, 20.91]), and L_{Aeq} also increases by 0.961 dB (BC 95% CI [.842, 1.094]). This is probably because more lanes indicate greater traffic demand generated by connected urban land, with the resultant higher traffic volume raising the level of traffic noise. The second greatest effect is the pathway via speed: each additional lane increases the group speed by 1.56 km/h (BC 95% CI [0.890, 2.247]), and L_{Aeq} also increases by 0.251 dB (BC 95% CI [0.139, 0.379]). The weakest effect is the pathway via the NVG and group speed, which is significantly less than the other two pathways, and was mainly used to improve the fitness index. In addition, effects from the

remaining pathways via the NVG and group speed are significant but weak; therefore, none of them are analysed below.

Table 6 lists the parameter estimates and confidence intervals of the effect of LN on $L_{10}-L_{90}$. The TE of the LN on noise amplitude is negative and significant. For each additional lane, $L_{10}-L_{90}$ decreases by 0.764 dB (BC 95% CI [-0.909, -0.620]). Both the DE and TIE are also negative and significant, but the difference between them is not. In terms of DE, this is because a greater number of lanes leads to less chaotic driving behaviour and vehicles travel more smoothly; thus, noise amplitude is smaller.

Within the TIE, three SIEs are significant. The greatest effect is the pathway via the NVG: each additional lane increases the NVG by 19.33 vehicles (BC 95% CI [17.79, 20.91]), thereby reducing $L_{10}-L_{90}$ by 0.404 dB (BC 95% CI [-0.557, -0.262]). The second greatest effect is the pathway via speed: each additional lane increases the group speed by 1.56 km/h (BC 95% CI [.890, 2.247]), thereby reducing $L_{10}-L_{90}$ by 0.043 dB (BC 95% CI [-.095, -.007]).

Table 6. Unstandardized direct effect (DE), total indirect effect (TIE), total effect (TE), and specific indirect effect (SIE) of lane number (LN) on $L_{10}-L_{90}$.

LN → $L_{10}-L_{90}$	Point Estimate	Product of coefficients		Bootstrap 5,000 times 95% CI					
		SE	Z	Bias corrected			Percentile		
				Lower	Upper	p	Lower	Upper	p
DE & TIE & TE									
DE	-.346	.112	-3.089	-.556	-.122	.002	-.560	-.127	.002
TIE	-.418	.076	-5.500	-.575	-.276	.000	-.572	-.272	.000
TE	-.764	.074	-10.324	-.909	-.620	.000	-.905	-.618	.000
TIE vs. DE	-.073	.177	-.412	-.432	.262	.681	-.427	.266	.696
SIE									
S1. LN → NVG → $L_{10}-L_{90}$	-.404	.075	-5.387	-.557	-.262	.000	-.554	-.257	.000
S2. LN → Speed → $L_{10}-L_{90}$	-.043	.022	-1.955	-.095	-.007	.019	-.091	-.004	.028
S3. LN → NVG → Speed → $L_{10}-L_{90}$.028	.015	1.867	.006	.066	.015	.003	.061	.028
Contrast between SIE									
S1 vs. S2	-.361	.077	-4.688	-.522	-.217	.000	-.515	-.213	.000
S1 vs. S3	-.432	.077	-5.610	-.597	-.289	.000	-.588	-.283	.000
S2 vs. S3	-.071	.035	-2.029	-.155	-.013	.019	-.149	-.007	.028

Note. DE: direct effect; TIE: total indirect effect; TE: total effect; SIE: specific indirect effect; LN: lane number; NVG: number of vehicles in a group.

3.4. Effect of road segment length on noise

Table 7 lists the parameter estimates and confidence intervals for the effect of RSL on L_{Aeq} . The TE of road length on noise intensity is positive and significant: each additional 10 m of road segment increases L_{Aeq} by 0.060 dB (BC 95% CI [0.010, 0.110]). The influence of RSL on traffic noise mainly depends on traffic flow changes since DE is not significant.

Within the TIE, three SIEs are significant, and the two main effects are in opposite directions. The greatest effect is the pathway via speed: each additional 10 m increases the group speed by 0.54 km/h (BC 95% CI [0.355, 0.722]), thereby increasing the L_{Aeq} by 0.087 dB (BC 95% CI [0.058, 0.117]). The second greatest effect is the pathway via the

NVG: for each additional 10 m, the NVG is reduced by 0.81 vehicles (BC 95% CI [-1.118, -0.505]), thereby reducing the L_{Aeq} by 0.040 dB (BC 95% CI [-0.056, -0.026]). This is probably because longer roads allow easier dispersions in the traffic flow. Thus, for the same average speed, fewer vehicles in a group generate less noise.

Table 7. Unstandardized direct effect (DE), total indirect effect (TIE), total effect (TE), and specific indirect effect (SIE) of road segment length (RSL) on L_{Aeq} .

RSL → L_{Aeq}	Point Estimate	Product of coefficients		Bootstrap 5,000 times 95% CI					
		SE	Z	Bias corrected			Percentile		
				Lower	Upper	p	Lower	Upper	p
DE & TIE & TE									
DE	.0006	.023	.261	-.0039	.0054	.753	-.0039	.0053	.786
TIE	.0053	.014	3.786	.0025	.0081	.000	.0025	.0081	.000
TE	.0060	.026	2.308	.0010	.0110	.020	.0010	.0110	.020
TIE vs. DE	.0047	.029	1.621	-.0012	.0103	.109	-.0011	.0104	.106
SIE									
S1. RSL → NVG → L_{Aeq}	-.0040	.008	-5.000	-.0056	-.0026	.000	-.0055	-.0025	.000
S2. RSL → Speed → L_{Aeq}	.0087	.015	5.800	.0058	.0117	.000	.0057	.0116	.000
S3. RSL → NVG → Speed → L_{Aeq}	.0007	.003	2.333	.0003	.0013	.000	.0003	.0013	.000
Contrast between SIE									
S1 vs. S2	-.0127	.019	-6.684	-.0167	-.0091	.000	-.0165	-.0089	.000
S1 vs. S3	-.0047	.010	4.700	-.0068	-.0030	.000	-.0067	-.0029	.000
S2 vs. S3	.0080	.015	5.333	.0051	.0110	.000	.0051	.0109	.000

Note. DE: direct effect; TIE: total indirect effect; TE: total effect; SIE: specific indirect effect; RSL: road segment length; NVG: number of vehicles in a group.

Table 8. Unstandardized direct effect (DE), total indirect effect (TIE), total effect (TE), and specific indirect effect (SIE) of road segment length (RSL) on L_{10} – L_{90} .

RSL → L_{10} – L_{90}	Point Estimate	Product of coefficients		Bootstrap 5,000 times 95% CI					
		SE	Z	Bias corrected			Percentile		
				Lower	Upper	p	Lower	Upper	p
DE & TIE & TE									
DE	-.0059	.034	-1.735	-.0125	.0010	.089	-.0127	.0008	.081
TIE	.0001	.008	.125	-.0015	.0016	.902	-.0015	.0017	.891
TE	-.0058	.034	-1.706	-.0122	.0010	.101	-.0125	.0008	.087
TIE vs. DE	.0060	.036	1.667	-.0012	.0130	.099	-.0010	.0131	.091
SIE									
S1. RSL → NVG → L_{10}–L_{90}	.0017	.004	4.250	.0010	.0027	.000	.0009	.0026	.000
S2. RSL → Speed → L_{10}–L_{90}	-.0015	.007	-2.143	-.0031	-.0003	.018	-.0030	-.0002	.028
S3. RSL → NVG → Speed → L_{10}–L_{90}	-.0001	.001	-1.000	-.0003	.0000	.011	-.0003	.0000	.028
Contrast between SIEs									
S1 vs. S2	.0032	.009	3.556	.0017	.0051	.000	.0015	.0050	.000
S1 vs. S3	.0018	.005	3.600	.0010	.0029	.000	.0010	.0028	.000
S2 vs. S3	-.0014	.005	-2.800	-.0029	-.0003	.017	-.0028	-.0001	.028

Note. DE: direct effect; TIE: total indirect effect; TE: total effect; SIE: specific indirect effect; RSL: road segment length; NVG, number of vehicles in a group.

Table 8 lists the parameter estimates and confidence intervals for the effect of RSL on L_{10} – L_{90} . The TE, DE, and TIE of the RSL on L_{10} – L_{90} are not significant. However, the three SIEs are significant. The two major SIEs occur in opposite directions and their effects are similar; thus, the TIE is not significant due to suppression effects. Each additional 10 m

increases the group speed by 0.54 km/h (BC 95% CI [0.355, 0.722]), thereby reducing $L_{10}-L_{90}$ by 0.015 dB (BC 95% CI [-0.031, -0.003]). Meanwhile, each additional 10 m reduces the NVG by 0.81 vehicles (BC 95% CI [-1.118, -0.505]), thereby increasing $L_{10}-L_{90}$ by 0.017 dB (BC 95% CI [0.010, 0.027]).

3.5 Effect of road junction on noise

Table 9 lists the parameter estimates and confidence intervals for the effect of RJ on L_{Aeq} . The absence of traffic lights has a significant effect on the L_{Aeq} , which is 0.556 dB (BC 95% CI [0.056, 1.060]) higher than that in the presence of traffic lights. The DE and TIE are significant, with opposite effects, and the DE is significantly weaker than the TIE.

For the DE, noise in the absence of traffic lights is 0.561 dB lower than that in the presence of traffic lights (BC 95% CI [-1.012, -0.128]), indicating that the installation of traffic lights can increase noise, independent of changes in the traffic flow. In the TIE, noise in the absence of traffic lights is 1.117 dB higher than that in the presence of traffic lights (BC 95% CI [0.828, 1.464]).

Table 9. Unstandardized direct effect (DE), total indirect effect (TIE), total effect (TE), and specific indirect effect (SIE) of road junction (RJ) on L_{Aeq} .

RJ→ L_{Aeq}	Point Estimate	Product of coefficients		Bootstrap 5,000 times 95% CI					
		SE	Z	Bias corrected			Percentile		
				Lower	Upper	p	Lower	Upper	p
DE & TIE & TE									
DE	-0.561	.223	-2.516	-1.012	-.128	.010	-1.015	-.129	.009
TIE	1.117	.165	6.770	.828	1.464	.000	.821	1.457	.000
TE	.556	.258	2.155	.056	1.060	.031	.054	1.058	.032
TIE vs. DE	1.678	.296	5.669	1.111	2.281	.000	1.119	2.287	.000
SIE									
S1. RJ→ NVG → L_{Aeq}	.472	.097	4.866	.297	.683	.000	.292	.674	.000
S2. RJ→ Speed → L_{Aeq}	.727	.164	4.433	.432	1.076	.000	.429	1.068	.000
S3. RJ→ NVG → Speed → L_{Aeq}	-0.081	.033	-2.455	-0.164	-0.031	.000	-0.159	-0.030	.000
Contrast between SIEs									
S1 vs. S2	-0.255	.203	-1.256	-0.664	.130	.194	-0.668	.128	.190
S1 vs. S3	.552	.125	4.416	.335	.829	.000	.327	.819	.000
S2 vs. S3	.807	.167	4.832	.510	1.165	.000	.508	1.160	.000

Note. DE: direct effect; TIE: total indirect effect; TE: total effect; SIE: specific indirect effect; RJ: road junction; NVG: number of vehicles in a group.

Within the TIE, three SIEs are significant. In the pathway via the group speed, the absence of traffic lights increases the group speed by 4.52 km/h (BC 95% CI [2.789, 6.365]), thereby increasing the L_{Aeq} by 0.727 dB (BC 95% CI [0.432, 1.076]). In the pathway via the NVG, the absence of traffic lights increases the NVG by 9.49 vehicles (BC 95% CI [6.030, 13.235]), thereby increasing the L_{Aeq} by 0.472 dB (BC 95% CI [0.297, 0.683]).

Table 10 lists the parameter estimates and confidence intervals for the effect of RJ on $L_{10}-L_{90}$. The TE of the RJ on $L_{10}-L_{90}$ is significant, and noise in the absence of traffic lights is 1.652 dB (BC 95% CI [-2.073, -1.225]) lower than that in the presence of traffic lights.

The DE and TIE are significant, and the DE is significantly stronger than the TIE. In terms of the DE, $L_{10}-L_{90}$ in the absence of traffic lights is 1.344 dB (BC 95% CI [-1.766, -0.911]) lower than that in the presence of traffic lights. In terms of the TIE, $L_{10}-L_{90}$ in the absence of traffic lights is 0.308 dB (BC 95% CI [-0.466, -0.180]) lower than that in the presence of traffic lights.

Within the TIE, three SIEs are significant. For the pathway via the group speed, the absence of traffic lights increases the speed by 4.52 km/h (BC 95% CI [2.789, 6.365]), thereby reducing $L_{10}-L_{90}$ by 0.124 dB (BC 95% CI [-0.269, -0.021]). For the pathway via the NVG, the absence of traffic lights increases the NVG by 9.49 vehicles (BC 95% CI [6.030, 13.235]), thereby reducing $L_{10}-L_{90}$ by 0.198 dB (BC 95% CI [-0.306, -0.122]).

RJ has a significant direct effect on both L_{Aeq} and $L_{10}-L_{90}$, and will be analysed in the next section. However, the significant TIEs and SIEs of the RJ on the L_{Aeq} and $L_{10}-L_{90}$ are more difficult to explain. This is likely due to the complex methods associated with traffic signal control. Therefore, further research is required.

Table 10. Unstandardized direct effect (DE), total indirect effect (TIE), total effect (TE), and specific indirect effect (SIE) of road junction (RJ) on $L_{10}-L_{90}$.

RJ → $L_{10}-L_{90}$	Point Estimate	Product coefficients of		Bootstrap 5,000 times 95% CI					
		SE	Z	Bias corrected			Percentile		
				Lower	Upper	p	Lower	Upper	p
DE & TIE & TE									
DE	-1.344	.216	-6.222	-1.766	-.911	.000	-1.766	-.911	.000
TIE	-.308	.072	-4.278	-.466	-.180	.000	-.457	-.171	.000
TE	-1.652	.214	-7.720	-2.073	-1.225	.000	-2.077	-1.228	.000
TIE vs. DE	1.036	.239	4.335	.556	1.501	.000	.560	1.508	.000
SIE									
S1. RJ → NVG → $L_{10}-L_{90}$	-.198	.046	-4.304	-.306	-.122	.000	-.294	-.113	.000
S2. RJ → Speed → $L_{10}-L_{90}$	-.124	.063	-1.968	-.269	-.021	.020	-.260	-.013	.028
S3. RJ → NVG → Speed → $L_{10}-L_{90}$.014	.008	1.750	.003	.037	.014	.001	.033	.028
Contrast between SIEs									
S1 vs. S2	-.075	.078	-.962	-.217	.091	.342	-.217	.092	.349
S1 vs. S3	-.212	.050	-4.240	-.331	-.128	.000	-.317	-.121	.000
S2 vs. S3	-.137	.068	-2.015	-.293	-.022	.021	-.285	-.015	.028

Note. DE: direct effect; TIE: total indirect effect; TE: total effect; SIE: specific indirect effect; RJ: road junction; NVG: number of vehicles in a group.

3.6. Paired comparisons of scenarios

Paired comparison of scenarios use two methods: (1) microscopic traffic and noise simulation, and (2) macroscopic traffic simulation.

Five paired comparisons of scenarios were considered as typical examples to further validate the results through microscopic traffic and noise simulation, corresponding to the significant pathways (i.e., $LN \rightarrow speed \rightarrow L_{Aeq}$ and $L_{10}-L_{90}$, $LN \rightarrow NVG \rightarrow L_{Aeq}$ and $L_{10}-L_{90}$, $RSL \rightarrow speed \rightarrow L_{Aeq}$ and $L_{10}-L_{90}$, $RSL \rightarrow NVG \rightarrow L_{Aeq}$ and $L_{10}-L_{90}$, and $RJ \rightarrow L_{Aeq}$, and $L_{10}-L_{90}$).

First, only one road characteristic indicator was assigned differently, excluding the influence of the other two indicators. Second, among the traffic flow indicators, only the

mediated indicator could be changed according to the specified conditions, whereas the rest were fixed. Finally, microscopic traffic simulations were conducted, and traffic noise was calculated. The effect of LN on traffic noise is illustrated by the paired comparison of two and five lanes. The effect of RSL on traffic noise is illustrated by the paired comparison of RSLs with lengths of 150 and 300 m. The above pairings and other settings (see Table 11) can increase the effect of road characteristics on noise. It should be noted that to obtain a clearer LN trend, the scenario settings were not entirely based on the field measurement conditions.

Table 11. Setting details for five paired comparisons of scenarios in Vissim.

No.	Pathway	Paired comparisons of scenarios	Traffic flow variables	
			Fixed indicator	Unfixed indicator
1	LN→ NVG → L _{Aeq} /L ₁₀ -L ₉₀	Paired comparison of two- and five-lanes one-way, with NVG unfixed, speed fixed, and RSL of 150 m.	Speed: set the road speed limit to 30 km/h via Vissim. ^a	NVG: for two- and five-lanes, set to 7 and 54, respectively. ^b
2	LN→ Speed→ L _{Aeq} /L ₁₀ -L ₉₀	Paired comparison of two- and five-lanes one-way, with speed unfixed, NVG fixed, and RSL of 150 m.	NVG: set to 10. ^c	Speed: obtained via Vissim, according to the car-following model.
3	RSL→ NVG → L _{Aeq} /L ₁₀ -L ₉₀	Paired comparison of five-lanes one-way with RSL of 150 and 300 m, NVG unfixed, and speed fixed.	Speed: set the road speed limit to 30 km/h via Vissim. ^a	NVG: for RSL of 150 and 300 m, set to 24 and 10, respectively. ^d
4	RSL→ speed → L _{Aeq} /L ₁₀ -L ₉₀	Paired comparison of five-lanes one-way with RSL of 150 and 300 m, speed unfixed, and NVG fixed.	NVG: set to 24. ^e	Speed: obtained via Vissim, according to the car-following model.
5	RJ → L _{Aeq} /L ₁₀ -L ₉₀	Paired comparison of five-lanes one-way 150 m, with or without signal light in the outgoing direction. ^f	Speed: set the road speed limit to 30 km/h via Vissim. ^a NVG: set to 24. ^e	

Note. ^a30 km/h is roughly the measured average speed, controlled by a "desired speed decision" in the Vissim simulation; ^b To be as close as possible to the field measurement, NVG was set based on measured data: 7 is the average NVG of two-lanes and 54 is the average NVG of five-lanes; ^c As close as possible to 7, which is the average NVG of two-lanes, while adhering to the group vehicle criteria, i.e., "the average number of vehicles per lane in the group is greater than one"; ^d According to the result "each additional 10 m reduced the NVG by 0.81 vehicles," it can be estimated that the difference between RSL at 300 and 600 m is 12. The NVG of 300 m RSL was set to 24 to make the effect that road characteristics had on noise more visible; ^e Reference d; ^f In the scenario without a signal light, a two-lane vertical road was set at the end of the road section as the priority traffic direction with 1,000 vehicles per hour.

Based on the methods used for field measurements, the receiving point was set in the middle of the road segment, data for each vehicle's driving status at each simulation time step was obtained, and traffic noise was calculated accordingly. Additionally, speed of the passage of each vehicle was recorded by a 'data collection point'. Finally, for each paired comparison of scenarios, the percent changes in the four indicators were calculated based on the four simulations, including the average passing vehicle speed (V_{avg}), standard deviation of the passing vehicle speed (V_{sd}), L_{Aeq} , and $L_{10}-L_{90}$. The parameter V_{sd} reflects the traffic flow stability (Jiang et al., 2017). Larger V_{sd} values result in lower traffic flow stability and vice versa. An example of the scenario settings with a signal in paired comparison No. 5 is shown in Fig. 6.

Signal light was required in all scenarios at the beginning and end of a road segment, except for scenarios where it was unable to be set. Signal lights at the beginning of a road segment are mainly meant to control the NVG by adjusting the signal timing. Signal lights placed at the end of a road segment have the same timing as the signals at the beginning of the road segment. The phase difference between the two signal lights is adjusted such that the vehicle encounters a red light when it reaches the end but all vehicles pass through during the next green light. The expected vehicle speed limit was set to 30 ± 10 km/h based on field measurement data. To obtain a more general conclusion, vehicles used for the traffic simulations were all light vehicles because the occurrence of heavy vehicles was too random. To collect a sufficient amount of vehicle data, calculations at a resolution of 10 time steps per simulation second were performed, with a duration of dozens of seconds depending on the traffic flow. A series of 0.1-s resolution sound pressure levels were obtained from the simulations. L_{Aeq} , L_{10} , L_{50} , and L_{90} were then calculated.

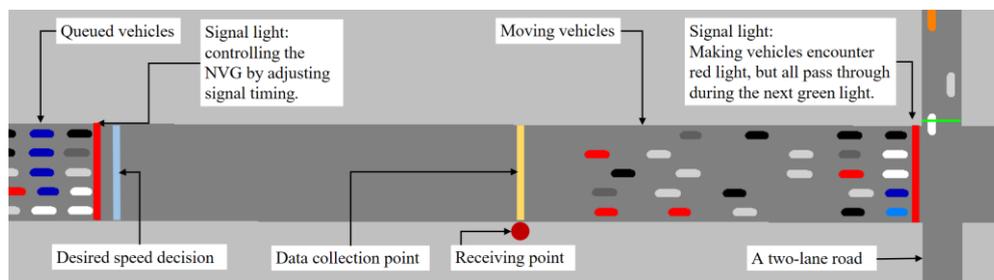


Fig. 6. Example scenario setting for paired comparison No. 5.

The units and ranges of the four indicators were not identical and cannot be directly compared. Thus, the percent change in each indicator for each paired comparison was discussed since the focus is to identify trends in the changes. As shown in Fig. 7, the trends in noise changes are consistent with previous conclusions based on statistical analysis. The specific analysis for each pathway is as follows.

The effect of LN on L_{Aeq} and L_{10} - L_{90} via NVG (LN→NVG→ L_{Aeq} and L_{10} - L_{90}): based on the assumption that vehicle speed is fixed, an increase in the LN increases the L_{Aeq} , which is clearly due to the increase in the NVG, as shown in Fig. 7(a). The decrease in L_{10} - L_{90} is caused by an increase in the NVG, which has a strong influence on background noise (L_{90}) and a weak influence on peak noise (L_{10}).

The effect of LN on L_{Aeq} and L_{10} - L_{90} via speed (LN→speed→ L_{Aeq} and L_{10} - L_{90}): based on the assumption that the NVG is fixed, an increase in the LN increases L_{Aeq} owing to the fact that the presence of more lanes enables higher speeds, which increases the noise levels, as shown in Fig. 7(b). Meanwhile, L_{10} - L_{90} decreases because as V_{avg} increases, abnormal driving behaviours, such as acceleration, deceleration, and lane-changing, decrease within the group, resulting in decreases in V_{sd} . This indicates that as vehicles travel more smoothly, traffic flow becomes more orderly and L_{10} - L_{90} decreases.

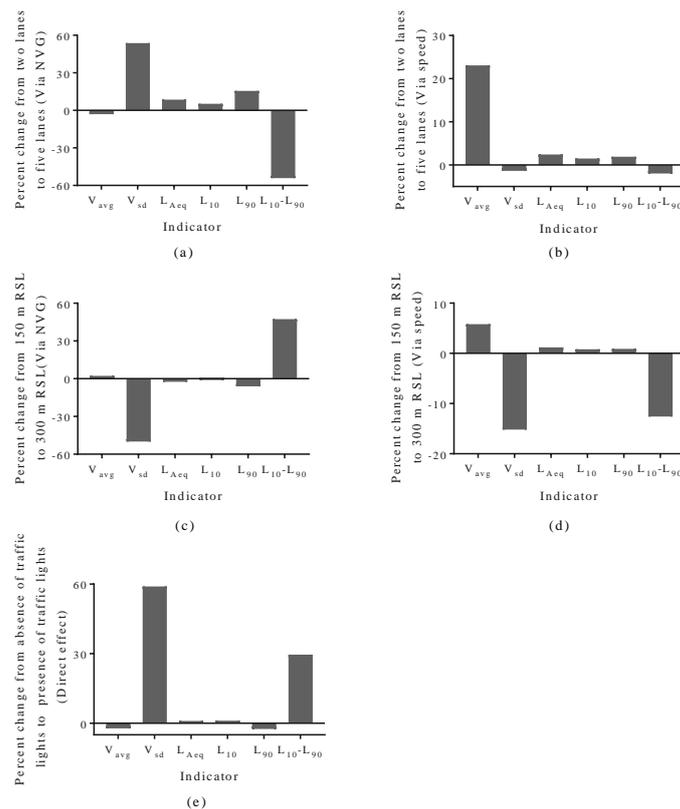


Fig. 7. Percent change in each indicator for each paired comparison of scenarios. (a) LN → NVG → L_{Aeq} & $L_{10}-L_{90}$, (b) LN → speed → L_{Aeq} & $L_{10}-L_{90}$, (c) RSL → NVG → L_{Aeq} & $L_{10}-L_{90}$, (d) RSL → speed → L_{Aeq} & $L_{10}-L_{90}$, and (e) RJ → L_{Aeq} & $L_{10}-L_{90}$.

The effect of RSL on L_{Aeq} and $L_{10}-L_{90}$ via NVG (RSL→NVG→ L_{Aeq} and $L_{10}-L_{90}$): based on the assumption that the vehicle speed is fixed, an increase in the RSL increases the L_{Aeq} , which is clearly due to the decrease in the NVG, as shown in Fig. 7(c). Meanwhile, $L_{10}-L_{90}$ also increases because the change in the NVG has different effects on the background (L_{90}) and peak noise (L_{10}).

The effect of RSL on L_{Aeq} and $L_{10}-L_{90}$ via speed (RSL→speed→ L_{Aeq} and $L_{10}-L_{90}$): based on the assumption that NVG is fixed, an increase in the RSL increases the L_{Aeq} because an increase in road length leads to increased group speed and noise, as shown in Fig. 7(d). The decrease in $L_{10}-L_{90}$ also indicates that changes in speed likely affect the orderliness of traffic flow, resulting in a decrease in V_{sd} .

The direct effect of RJ on L_{Aeq} and $L_{10}-L_{90}$ ((RJ→ L_{Aeq} and $L_{10}-L_{90}$)): based on the assumption that NVG and speed are fixed, the presence of traffic lights increases the L_{Aeq} because traffic lights are more likely to encourage the driver to accelerate or decelerate (as applicable) and drastically increase the V_{sd} , thereby generating more noise, as shown in Fig. 7(e). The presence or deceleration leads to considerable disorder in the vehicle driving state, as well as an increase in $L_{10}-L_{90}$.

Furthermore, the results were explored using control delay. HCS can accurately obtain control delay, but it is difficult to obtain the corresponding noise levels. Therefore, using the control delay as the independent variable instead of noise indicators in each pathway, paired comparisons of scenarios were considered as typical examples in HCS. In this way, the delay obtained by HCS simulation can be compared with the noise level obtained by statistical analysis, and the relationship between delay and noise can be determined.

Among five significant pathways, there were two pathways (LN→Speed→Delay and RJ→Delay) that could be analysed for control delay. The effects of RSL on the delay can be varied by the signal cycle and were therefore not analysed. For example, even with different RSL, minimally delayed traffic flow can be achieved in one direction through a series of coordinated traffic lights (i.e., green waves). The pathways via NVG were not analysed as well, partly because the indicator that reflects traffic volume in HCS is flow rate (veh/h) instead of NVG, which cannot be estimated from the changing road characteristics in this study; partly because the speed cannot be accurately fixed in HCS.

The All-Way Stop-Controlled (AWSC) module was used for the scenario of a road junction without traffic lights (i.e., a non-signalized intersection), and the Streets module was used for other scenarios in HCS. The road speed limit was uniformly set at 60 km/h, and running speed was automatically calculated according to a platoon dispersion mode (Forde and Daniel, 2017). All signals cycles were 80s and completely synchronous, and the duration of the green light and yellow light for the study road was always set to a half cycle. The other settings in the scenario were as follows: one-way road, no slope, no heavy vehicle, 0.25-h analysis duration (Table. 12). The flow rates in the scenarios were set to three conditions, while ensuring control delays of less than 40 s/veh, meaning that LOS at intersections ranged from level A to level D, which is the acceptable level range. The average control delay was calculated under three conditions for each scenario. Then, the percent change of control delay for each paired comparison was discussed, as shown in Fig. 8. Specific analysis for each pathway is as follows.

Table 12. Setting details for two paired comparisons of scenarios in the Highway Capacity Software (HCS).

No.	Pathway	Paired comparison of scenarios	Traffic flow variables	
			Fixed indicator	Unfixed indicator
1	LN→ Speed → Delay	Paired comparison of two- and five-lanes one-way, with flow rate fixed, speed unfixed, and road segment length (RSL) of 150 m.	Flow rate: set to 1000, 1400, 1800 veh/h for each road, respectively.	Speed: obtained via HCS, according to a platoon dispersion mode.
2	RJ → Delay	Paired comparison of two-lanes one-way, with or without signal light. Another perpendicular one-lane road set at intersection.	Flow rate: set to 400, 500, 600 veh/h for each lane, respectively. Speed: Models do not contain segment, no interval speed	

The effect of LN on delay via speed (LN→Speed→Delay): based on the assumption that traffic volume is fixed, increasing LN will reduce the delay and increase the L_{Aeq} , as shown in Fig. 8(a). This is consistent with analysis of Vissim simulations, and is because the increase in LN increases the road capacity, reducing the delay (average control delay reduced from 17.2 to 9.5 s/veh), which in turn increases the speed (average running speed increased from 40.5 to 43.2 km/h) and noise.

The direct effect of RJ on delay (RJ→Delay): based on the assumption that traffic volume and speed are fixed, the presence of traffic lights will reduce delay, and increase the L_{Aeq} , as shown in Fig. 8(b). This is consistent with the analysis of Vissim simulations, and is because setting a traffic light will enhance the road capacity and reduce delays (average control delay reduced from 25.4 to 17.4 s/veh), while encouraging vehicle acceleration and deceleration in the middle of the road segment, which in turn increases noise, since traffic lights allows a driver to judge the junction situation in advance.

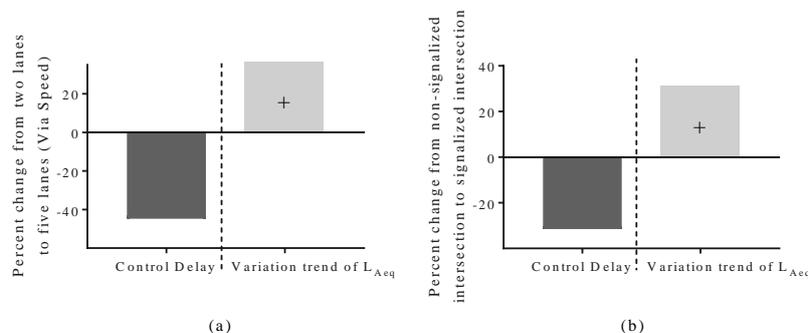


Fig. 8. Percent change in control delay for each paired comparison of scenarios. (a) LN → speed → Delay, (b) RJ → Delay.

Besides confirming the results obtained from statistical analysis, the macroscopic traffic simulation also found that reducing delays tends to increase noise intensity in the middle of the road segment. This relationship may change with location, for example, previous research found that in the sections of adjacent road junction, the greater the delay, the greater the noise intensity (Pal and Sarkar, 2012).

4. Discussion

Urban planning in China is paying more and more attention to traffic noise. Since 2009, the Chinese government has mandated planning design achievements, mainly including regulatory- and constructive-detailed planning, to allow for planning of environmental impact assessments (PEIA), within which traffic noise is one of the evaluation components. However, traffic noise is still rarely considered in urban planning and design in China. The PEIA only evaluates traffic noise planning achievements and proposes general suggestions, with minimal interaction with urban planners. Moreover, unlike Europe (Alves

et al., 2016), most cities do not have noise maps and suitable sound planning tools, which makes it difficult for planners to consider traffic noise during the planning design stage.

The influencing mechanism determined in this study can help planners better understand the relationships between road networks and traffic noise. For example, based on our results, each additional lane increases the average NVG of each lane by approximately 50%, which shows that the pathway through the NVG has the greatest LN effect on traffic noise. This is because traffic organisation and management actively guides vehicles into higher hierarchy roads, largely characterised by LN, to achieve improved vehicle flow with higher speeds and less congestion.

The parameter estimates reported in this study can be used as a local noise estimation model. In the urban planning stage, this type of model can help traffic noise assessments through an analysis of design information rather than complex acoustic calculations and simulations. For example, for the current scenario (i.e., road segment No.13 as shown in Fig. 9a), if the road characteristics change, the noise value can be predicted for local urban planning according to the total effect reported in this study. The road is cancelled, and thus the length of the segment increases by 150 m, as shown in Fig. 9(b), L_{Aeq} increases by 0.9 dB (0.0060×150), and $L_{10}-L_{90}$ decreases by 0.87 dB (0.0058×150). The traffic signal in the driving direction is further cancelled, such that L_{Aeq} decreases by 0.6 dB and $L_{10}-L_{90}$ increases by 1.6 dB, as shown in Fig. 9(c).

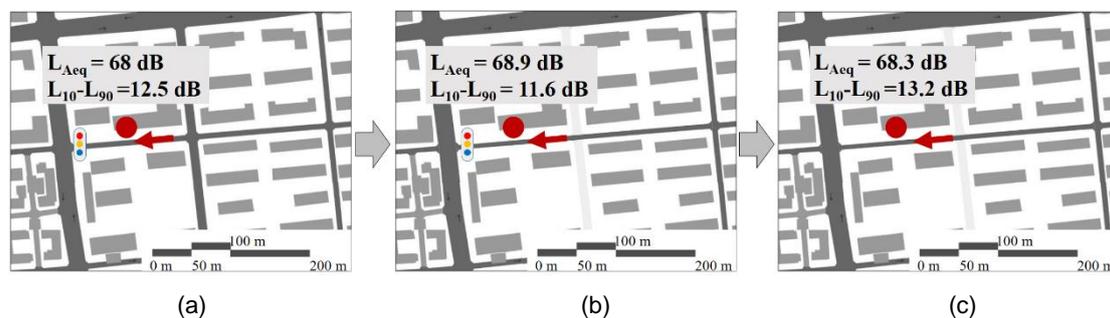


Fig. 9. Example of noise estimation for changes in road characteristics. (a) Current scenario of the road network and measured average noise value; (b) scenario with the cancelation of a vertical road along with the corresponding noise estimation; and (c) scenario with the cancelation of a vertical road and traffic light along with the corresponding noise estimation.

In addition, this study can also help amend PEIA predictions based on the road characteristics. In China, traffic noise PEIAs mostly use commercial noise prediction software. Detailed traffic flow data is a prerequisite for accurate simulations, which is difficult to obtain in China. China's road network is changing rapidly and many urban planning projects are faced with undeveloped land. Owing to the large gap between existing and future traffic data, PEIAs usually rely on forecast data for a certain period in the future (5, 10, or 20 years). For a long-distance road, the assigned traffic data and traffic

noise predictions are often identical. With the discussion provided in this study and through the analysis of design information, prediction results can be modified based on the road characteristics, allowing for more accurate urban planning initiatives.

5. Conclusions

In this study, the influence of road characteristics on traffic noise with traffic flow as a mediator was investigated using field noise measurements along typical road segments in China. Microscopic and macroscopic traffic simulations for paired comparisons of scenarios, were performed to conform to the needs of urban planning. The results show that:

- 1) The greatest effect of the lane number on traffic noise is the pathway through the number of vehicles in a group. A higher number of lanes indicates greater traffic demand due to more connected urban land, with a resulting increase in traffic volume and noise intensity. This has a strong and weak influence on background noise (L_{90}) and peak noise (L_{10}), respectively, thereby decreasing noise amplitude.
- 2) The effect that the RSL has on traffic noise mainly depends on the suppression effect. An increase in road length results in higher vehicle speed, leading to higher noise intensity and reduced noise amplitude. Simultaneously, an increase in the road length leads to a smaller number of vehicles in a group, which reduces noise intensity and increases noise amplitude.
- 3) Road junctions, which are classified according to the presence or absence of traffic lights, have a significant direct effect on both noise intensity and amplitude. The presence of traffic lights increases noise intensity because they are more likely to encourage drivers to accelerate or decelerate in the middle of the road segment. The acceleration and deceleration associated with traffic lights leads to considerable disorder in a vehicle's momentum, which increases noise amplitude.

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Table A.1. The runs test for each measurement point

Road Name	NVG	Speed	HVP	LAeq	L10	L50	L90	L10-L90
NO.01- Test Value ^a	108.0000000	24.5800000	.0700000	74.2000000	76.5000000	73.3000000	70.5000000	6.0000000
ZS								
Cases < Test Value	19	19	15	18	18	19	19	19
Cases >= Test Value	20	20	24	21	21	20	20	20
Total Cases	39	39	39	39	39	39	39	39
Number of Runs	15	15	24	21	22	18	16	22
Z	-1.620	-1.620	1.387	.038	.364	-.645	-1.295	.329
Asymp. Sig. (2-tailed)	.105	.105	.166	.970	.716	.519	.195	.742
NO.02- Test Value ^a	4.0000000	35.0100000	.0000000 ^b	71.3000000	73.0000000	71.0000000	69.1000000	4.7000000
FN								
Cases < Test Value	20	19	0	20	19	20	20	18
Cases >= Test Value	21	22	41	21	22	21	21	21
Total Cases	41	41	41	41	41	41	41	41
Number of Runs	16	20	1 ^b	19	25	18	16	21
Z	-1.579	-.283		-.629	.989	-.946	-1.579	.000
Asymp. Sig. (2-tailed)	.114	.777		.529	.323	.344	.114	1.000
NO.03- Test Value ^a	58.5000000	38.4650000	.1100000	74.4500000	76.8500000	73.0000000	68.3500000	8.4000000
TY								
Cases < Test Value	20	20	16	20	20	19	20	18
Cases >= Test Value	20	20	24	20	20	21	20	22
Total Cases	40	40	40	40	40	40	40	40
Number of Runs	17	18	16	21	23	21	23	25
Z	-1.121	-.801	-1.236	.000	.481	.000	.481	1.198
Asymp. Sig. (2-tailed)	.262	.423	.216	1.000	.631	1.000	.631	.231
NO.04- Test Value ^a	2.0000000 ^b	35.0350000	.0000000 ^b	69.4500000	72.5000000	68.0500000	65.3000000	8.7500000
JX								
Cases < Test Value	0	3	0	3	3	3	3	3
Cases >= Test Value	6	3	6	3	3	3	3	3
Total Cases	6	6	6	6	6	6	6	6
Number of Runs	1 ^c	5	1 ^c	5	5	5	3	4
Z		.456		.456	.456	.456	-.456	.000
Asymp. Sig. (2-tailed)		.648		.648	.648	.648	.648	1.000
NO.05- Test Value ^a	43.0000000	31.8100000	.1000000	73.3500000	75.4500000	72.0500000	68.8000000	6.9500000
FF1								
Cases < Test Value	18	18	17	18	18	18	17	18
Cases >= Test Value	18	18	19	18	18	18	19	18
Total Cases	36	36	36	36	36	36	36	36
Number of Runs	8	18	17	18	19	15	19	15
Z	-3.551	-.169	-.490	-.169	.000	-1.184	.000	-1.184
Asymp. Sig. (2-tailed)	.000	.866	.624	.866	1.000	.237	1.000	.237
NO.06- Test Value ^a	54.5000000	33.8500000	.0700950	75.1000000	77.7000000	74.0000000	69.3500000	8.5500000
GRJ1								
Cases < Test Value	28	27	28	27	26	27	28	28
Cases >= Test Value	28	29	28	29	30	29	28	28
Total Cases	56	56	56	56	56	56	56	56
Number of Runs	16	26	26	25	24	23	25	31
Z	-3.506	-.801	-.809	-1.071	-1.317	-1.611	-1.079	.539
Asymp. Sig. (2-tailed)	.000	.423	.418	.284	.188	.107	.281	.590
NO.07- Test Value ^a	22.0000000	29.2550000	.0850000	72.6500000	74.9000000	71.7500000	67.6500000	7.3500000
BS2								
Cases < Test Value	17	18	18	18	18	18	18	18
Cases >= Test Value	19	18	18	18	18	18	18	18
Total Cases	36	36	36	36	36	36	36	36
Number of Runs	14	12	23	17	21	15	20	22
Z	-1.508	-2.198	1.184	-.507	.507	-1.184	.169	.845
Asymp. Sig. (2-tailed)	.132	.028	.237	.612	.612	.237	.866	.398
NO.08- Test Value ^a	15.0000000	38.5050000	.0342105	71.3000000	73.9000000	70.1500000	65.1500000	8.7000000
BS1								
Cases < Test Value	19	19	19	19	18	19	19	18
Cases >= Test Value	19	19	19	19	20	19	19	20
Total Cases	38	38	38	38	38	38	38	38
Number of Runs	9	25	17	19	19	15	21	18
Z	-3.454	1.480	-.822	-.164	-.148	-1.480	.164	-.477
Asymp. Sig. (2-tailed)	.001	.139	.411	.869	.883	.139	.869	.633
NO.09- Test Value ^a	6.0000000	23.6400000	.0000000 ^b	68.8000000	71.8000000	68.0000000	62.8000000	9.6000000
WS1								
Cases < Test Value	20	22	0	21	22	22	22	22
Cases >= Test Value	25	23	45	24	23	23	23	23
Total Cases	45	45	45	45	45	45	45	45
Number of Runs	19	14	1 ^c	16	16	18	18	23
Z	-1.137	-2.712		-2.090	-2.109	-1.505	-1.505	.000
Asymp. Sig. (2-tailed)	.256	.007		.037	.035	.132	.132	1.000
NO.10- Test Value ^a	61.0000000	37.8900000	.0900000	74.8000000	76.8000000	73.0000000	69.6000000	7.6000000
FF2								
Cases < Test Value	15	11	13	15	15	14	14	15
Cases >= Test Value	16	20	18	16	16	17	17	16
Total Cases	31	31	31	31	31	31	31	31
Number of Runs	6	13	18	13	15	11	7	16
Z	-3.652	-.678	.527	-1.091	-.360	-1.791	-3.267	.000
Asymp. Sig. (2-tailed)	.000	.498	.598	.275	.719	.073	.001	1.000

Road Name	NVG	Speed	HVP	LAeq	L10	L50	L90	L10-L90
NO.11- Test Value ^a	128.0000000	39.9500000	.0600000	77.0000000	78.9000000	76.2000000	73.2000000	5.9000000
GRJ2 Cases < Test Value	14	14	12	13	14	14	14	14
Cases >= Test Value	15	15	17	16	15	15	15	15
Total Cases	29	29	29	29	29	29	29	29
Number of Runs	13	14	15	8	14	12	12	11
Z	-.751	-.372	.000	-2.618	-.372	-1.129	-1.129	-1.508
Asymp. Sig. (2-tailed)	.453	.710	1.000	.009	.710	.259	.259	.132
NO.12- Test Value ^a	18.0000000	30.4200000	.0000000 ^b	72.8000000	74.9000000	71.3000000	67.2000000	7.9500000
WS2 Cases < Test Value	21	19	0	21	22	21	20	22
Cases >= Test Value	23	25	44	23	22	23	24	22
Total Cases	44	44	44	44	44	44	44	44
Number of Runs	9	23	1 ^c	22	22	18	25	19
Z	-4.113	.000		-.139	-.153	-1.362	.517	-1.068
Asymp. Sig. (2-tailed)	.000	1.000		.889	.879	.173	.605	.286
NO.13- Test Value ^a	3.0000000	25.3900000	.0000000 ^b	67.9000000	71.4000000	65.9000000	59.3000000	12.1000000
MZ Cases < Test Value	17	21	0	22	21	22	22	22
Cases >= Test Value	28	24	45	23	24	23	23	23
Total Cases	45	45	45	45	45	45	45	45
Number of Runs	14	22	1 ^c	27	22	29	29	18
Z	-2.459	-.273		.909	-.273	1.512	1.512	-1.505
Asymp. Sig. (2-tailed)	.014	.785		.364	.785	.131	.131	.132
NO.14- Test Value ^a	3.0000000	28.8000000	.0000000 ^b	65.6000000	69.4000000	62.8000000	58.0000000	11.3000000
YP Cases < Test Value	10	11	0	10	11	11	11	11
Cases >= Test Value	13	12	23	13	12	12	12	12
Total Cases	23	23	23	23	23	23	23	23
Number of Runs	16	12	1 ^c	12	13	12	10	16
Z	1.389	.000		.000	.009	.000	-.846	1.292
Asymp. Sig. (2-tailed)	.165	1.000		1.000	.993	1.000	.398	.196
NO.15- Test Value ^a	4.0000000	15.1700000	.0000000 ^b	67.5500000	71.5500000	65.1000000	57.5500000	13.7500000
SC Cases < Test Value	15	21	0	21	21	21	21	21
Cases >= Test Value	27	21	42	21	21	21	21	21
Total Cases	42	42	42	42	42	42	42	42
Number of Runs	13	15	1 ^c	19	23	20	23	19
Z	-2.314	-2.031		-.781	.156	-.469	.156	-.781
Asymp. Sig. (2-tailed)	.021	.042		.435	.876	.639	.876	.435
NO.16- Test Value ^a	4.5000000	36.5500000	.0000000 ^b	70.6500000	73.7500000	68.6500000	63.0000000	10.2500000
YH Cases < Test Value	20	19	0	20	20	20	20	20
Cases >= Test Value	20	21	40	20	20	20	20	20
Total Cases	40	40	40	40	40	40	40	40
Number of Runs	16	22	1 ^c	16	18	16	15	27
Z	-1.442	.177		-1.442	-.801	-1.442	-1.762	1.762
Asymp. Sig. (2-tailed)	.149	.860		.149	.423	.149	.078	.078
NO.17- Test Value ^a	8.5000000	45.1700000	.0000000 ^b	72.7000000	75.8000000	71.1000000	66.3000000	9.9500000
NS1 Cases < Test Value	21	20	0	20	19	19	20	21
Cases >= Test Value	21	22	42	22	23	23	22	21
Total Cases	42	42	42	42	42	42	42	42
Number of Runs	15	20	1 ^c	21	19	24	20	20
Z	-2.031	-.455		-.142	-.728	.533	-.455	-.469
Asymp. Sig. (2-tailed)	.042	.649		.887	.466	.594	.649	.639
NO.18- Test Value ^a	6.5000000	39.6950000	.0000000 ^b	71.5500000	74.4500000	70.0000000	65.6000000	9.0500000
NS2 Cases < Test Value	13	13	0	13	13	12	13	13
Cases >= Test Value	13	13	26	13	13	14	13	13
Total Cases	26	26	26	26	26	26	26	26
Number of Runs	6	10	1 ^c	10	10	11	10	14
Z	-3.002	-1.401		-1.401	-1.401	-.976	-1.401	.000
Asymp. Sig. (2-tailed)	.003	.161		.161	.161	.329	.161	1.000
NO.19- Test Value ^a	13.0000000	40.5600000	.0400000	73.0000000	75.9000000	71.3000000	64.0000000	11.6000000
NS3 Cases < Test Value	18	19	19	20	20	18	19	20
Cases >= Test Value	23	22	22	21	21	23	22	21
Total Cases	41	41	41	41	41	41	41	41
Number of Runs	14	14	22	19	19	18	20	20
Z	-2.151	-2.192	.035	-.629	-.629	-.866	-.283	-.313
Asymp. Sig. (2-tailed)	.032	.028	.972	.529	.529	.387	.777	.755
NO.20- Test Value ^a	5.0000000	46.9500000	.0000000 ^b	74.0500000	76.8000000	72.6000000	69.1000000	7.0000000
QQ Cases < Test Value	17	21	0	21	20	20	20	19
Cases >= Test Value	25	21	42	21	22	22	22	23
Total Cases	42	42	42	42	42	42	42	42
Number of Runs	20	23	1 ^c	23	19	20	22	20
Z	-.240	.156		.156	-.768	-.455	.000	-.413
Asymp. Sig. (2-tailed)	.811	.876		.876	.442	.649	1.000	.680

a. Median
b. All values are greater than or less than the cut-off. Runs test cannot be performed.
c. Only one run occurs. Runs test cannot be performed.

Table A.2. Goodness-of-fit measures for SEM of other indicators of noise intensity (N = 742)

Fit indices	χ^2/df	RMSEA	CFI	IFI	TLI	GFI	AGFI
Recommended value	<2.00	<0.05	>0.90	>0.90	>0.90	>0.90	>0.90
Model E	1.698	0.031	0.999	0.999	0.990	0.999	0.982
Model F	1.698	0.031	0.999	0.999	0.991	0.999	0.982
Model G	1.698	0.031	0.999	0.999	0.990	0.999	0.982

Note. Model E: Structural equation model with L10 as the dependent variable; Model F: Structural equation model with L50 as the dependent variable; Model G: Structural equation model with L90 as the dependent variable.

Note. χ^2/df : chi square to df ratio; RMSEA: root-mean-square error of approximation; CFI: comparative fit index; IFI: incremental fit index; TLI: Tucker-Lewis index; GFI: goodness-of-fit index; AGFI, adjusted goodness-of-fit.

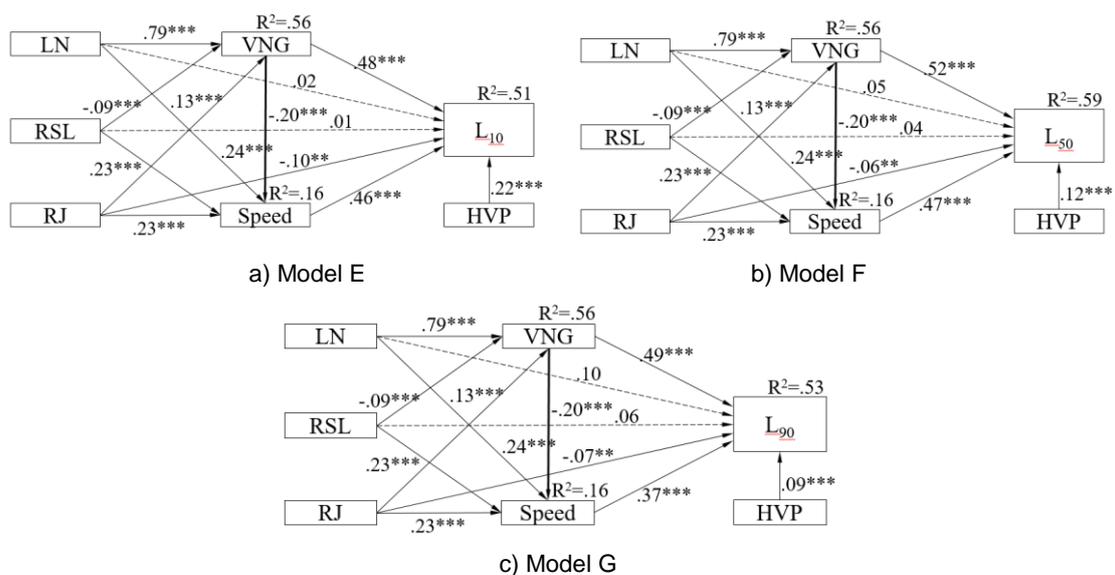


Fig. A.1. Structural equation models for other indicators of noise intensity

(a) Model E: Structural equation model with L₁₀ as the dependent variable; (b) Model F: Structural equation model with L₅₀ as the dependent variable; (c) Model G: Structural equation model with L₉₀ as the dependent variable.

Note. χ^2/df : chi square to df ratio; RMSEA: root-mean-square error of approximation; CFI: comparative fit index; IFI: incremental fit index; TLI: Tucker-Lewis index; GFI: goodness-of-fit index; AGFI, adjusted goodness-of-fit.