

Perceived integrated impact of visual intrusion and noise of motorways: influential factors and impact indicators

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Abstract

Motorways are often seen as intrusive to both landscape and soundscape, and recent studies on multisensory perception suggest that an integrated assessment of the environmental impacts is necessary. This paper investigates the effects of traffic condition, distance to road and background landscape on the perceived integrated impact of noise and visual intrusion of motorways, and explores if noise exposure can be a powerful indicator for the perceived integrated impact. Six traffic conditions, consisting of three levels of noise emission \times two levels of heavy good vehicle percentage in traffic composition, two types of background landscape and three distances to road, were designed as experimental scenarios, and created using computer visualisation and edited audio recordings. A laboratory experiment was carried out to obtain ratings of perceived environmental quality of each experimental scenario. The results show that traffic volume as expressed by noise emission level strongly influenced the perceived integrated impact, whereas traffic composition did not make noticeable differences. Distance to road was the second most influential factor, followed by background landscape. A regression model using noise level at receiver position and type of background landscape as independent variables was developed and can explain about a quarter of the variation in the perceived integrated impact.

Keywords: traffic noise; visual impact; motorway; multisensory perception

Transportation Research Part D: Transport and Environment, Volume 57, December 2017, Pages 217–223

Available online 04 October 2017

Introduction

Motorways are often seen as intrusive to both landscape and soundscape. Potential visual impact of motorways can be induced as deterioration in visual landscape quality caused by the presence of the massive roadway structure, as well as by the large volume of traffic moving on the roadway (Federal Highway Administration, 1981; Highways Agency, 2000). Research has shown that existing landscape, distance to road, traffic flow and composition can all have strong influence on the level of the perceived impact (Gigg, 1980; Hopkinson & Watson, 1974; Huddart, 1978; Jiang et al., 2015; Jiang & Kang, 2016). Permanent noise impact of motorways is caused by moving vehicles and the interaction of their tyres with the road surface, and can have severe harmful effects on human health and quality of life (Highways Agency, 2011). While measured noise exposure can be helpful indices of the noise climate, the level of the perceived impact is however also influenced by many non-acoustical factors (Jeon et al, 2011; Aletta et al. 2016).

Recently, research in environmental psychology has stressed the multisensory nature of human perception (Cassidy, 1997). Multisensory approach, especially addressing the aural-visual interaction, has been applied in many studies aiming to gain deeper understanding on environmental perception and develop human-centred methodologies for assessments of soundscape and landscape. While some studies investigated either the effect of visual stimuli on perception of sound environment (e.g., Liu et al., 2014; Ren & Kang, 2015; Viollon et al., 2002), or the effect of audio stimuli on perception of visual environment (e.g., Anderson et al. 1983; Benfield et al., 2010; Hetherington et al., 1993), many have focused on their interactive effects on perception of the overall environment (e.g., Carles et al, 1999; Hong & Jeon, 2013; Pheasant et al., 2008). Nilsson et al. (2012) argued that assessing the overall environmental quality might be easier and more natural than assessing environmental quality of each sensorial modality separately.

This might be particularly applicable for the assessments of visual and noise impacts of motorways, which means assessing the integrated impact of visual intrusion and noise on the overall environmental quality, since visual and noise impacts of motorways are very often coexistent and share some common influential factors. It would also be very helpful if strong relationships exist between the integrated impact and some well-developed visual and/or noise impact indicators. For instance, the Directive 2002/49/EC (European Parliament and Council, 2002) requires all EU member states to produce maps of exposure of environmental noise from major roads, railways and airports and in large urban areas, so a strong relationship between the integrated impact and noise exposure would enable assessment of the integrated impact using readily available data.

While a large amount of research have been conducted to investigate how possible influential factors affect the perceived visual or noise impacts of road projects, little

effect has been made for the perceived integrated impact of visual intrusion and noise. This paper is therefore aimed to investigate the possible effects of key factors, which have been shown to be influential on both perceived visual and noise impacts, on the perceived integrated impact of visual intrusion and noise of motorways. Specifically, this paper has two objectives: (1) investigates the effects of traffic condition, distance to road and background landscape on the perceived integrated impact of noise and visual intrusion of motorways; (2) explores if noise exposure can be a powerful indicator for the perceived integrated impact.

Section 2 of the paper describes in detail the experimental design and implementation. Section 3 presents the results of the experiment with discussion, and Section 4 concludes the paper.

2. Method

This paper used a laboratory experiment to obtain ratings of the perceived integrated impact in designed scenarios. Laboratory experiments have been commonly used for studies requiring multi-sensory perceptual evaluations for their advantages in scenario control with reliable validity (e.g., Carles et al., 1999; Hong & Jeon, 2013; Pheasant et al., 2008; Viollon et al., 2002).

2.1. Experimental design

Six traffic conditions, consisting of three levels of noise emission \times two levels of heavy good vehicle (HGV) percentage in traffic composition, were designed for this study. The three noise emission levels were 87.6 dB(A) L_{10} , 83.3 dB(A) L_{10} and 79.0 dB(A) L_{10} . The two HGV percentages were 10% and 20%. These values were determined based on the annual traffic count of UK motorways (Department for Transport, 2014; Highways Agency, 2004) and the UK motorway speed limits (GOV.UK, 2014). The general criteria was to make adequate variations while keep them representative and reasonable for a typical segment of motorways. Each of the three emission levels was kept constant for the two HGV percentage scenarios by changing the overall traffic flow, so the visual effect of traffic composition on the perceived impact can be tested. A baseline scenario without motorway was also added for comparisons that would be needed to calculate perceived impact (see Section 2.5).

Three distances to road, 100 m, 200 m and 300 m, were chosen for this study. The upper limit of 300 m was thought to be suitable for both visual and noise impacts. For visual impact, roads and traffic in foreground views (defined as within 0 to 400-800 m) are most potential to induce visual impact (Federal Highway Administration, 1981); for noise impact, the UK Noise Insulation Regulation has a within-300-m criterion for residential buildings to be eligible for grants for noise insulation (Department of the Environment, 1988). So 300 m would be a reasonable cut-off line for this study, although potential visual and noise impacts can reach much further beyond. Distances

shorter than 100 m were not covered in this study, since receiver positions too close to the edge of carriageways are less common in cases of motorways.

Two types of background landscape, natural and residential landscapes in a rural area, which are typical along motorway corridors in the UK, were designed for this study. A summary of the experimental scenarios are shown in Figure 1.

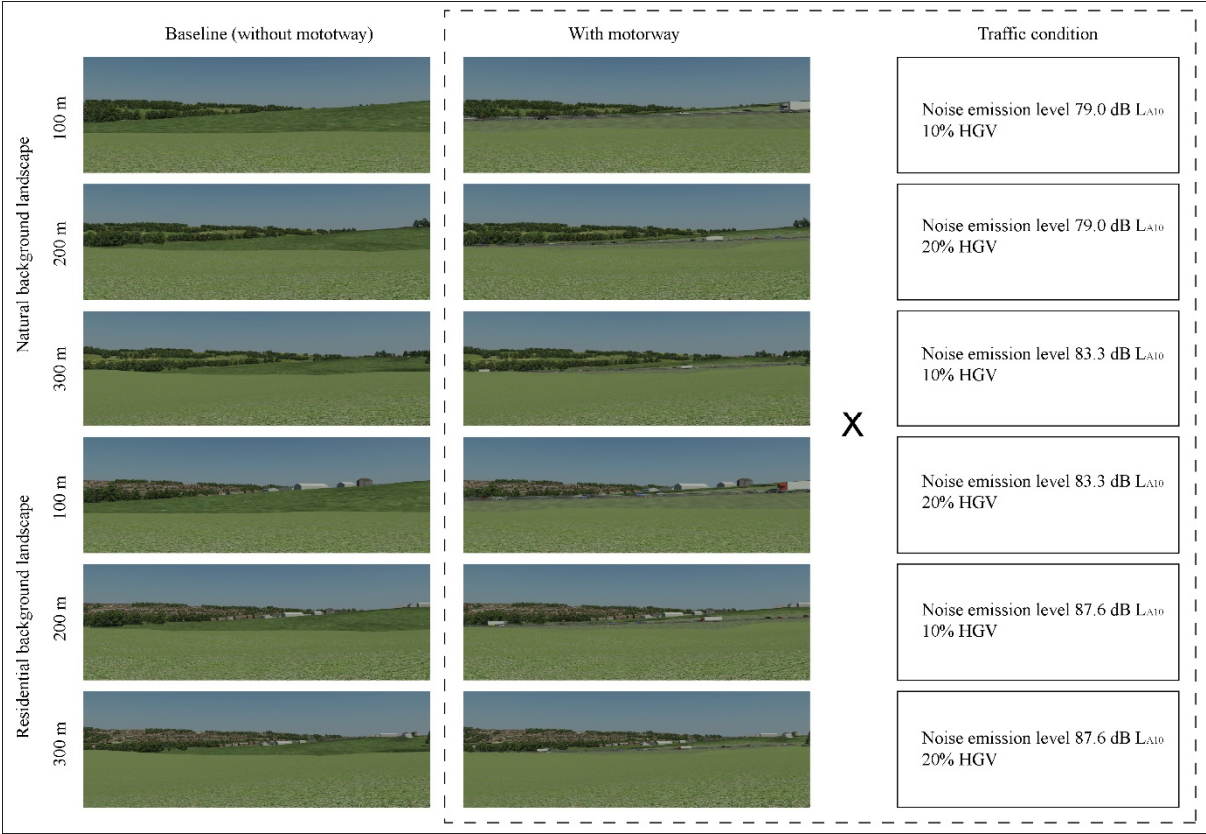


Figure 1. Summary of the experimental scenarios.

2.2. Preparation of visual stimuli

A site along a segment of the UK M1 motorway between Junction 34 and 35, covering an area of 2500 m × 2500 m, was chosen as the base site for computer visualisation. The motorway has three lanes plus a hard shoulder in each direction. With digital terrain model and land cover data of the site from Ordnance Survey, the motorway and its surrounding landscape were modelled in Autodesk 3ds Max Design. Based on this 3D model of the base site, the natural and residential landscape scenarios were created by changing the amounts of trees and buildings, the baseline scenarios were created by replacing the motorway with grassland.

Animations of moving vehicles were made for the six traffic conditions. The exact numbers of cars and HGVs for each traffic condition in 20 seconds, which was the length of each video scene that would be rendered, were calculated in CadnaA using the UK CRTN model (Department of Transport, 1988), and are shown in Table 1.

Three viewpoints, 100 m, 200 m and 300 m away respectively from the near edge of the motorway, were assigned in the models for the three distance scenarios. Cameras to capture views from the three viewpoints were set 1.6 m above the ground, facing perpendicular to the motorway and with the target of each camera set at the same height as the targeted road surface. These settings were chosen to simulate a viewer of normal height looking directly at the motorway, and thus to possibly obtain the view with maximum motorway visibility for each viewpoint, since in practice of visual impact assessment, it is suggested that visualisations should show the development to be assessed in conditions of maximum visibility (Landscape Institute & Institute of Environmental Management & Assessment, 2013). The horizontal field of view was set to be 72°, which is wider than that of a standard lens, to present the breadth of visual information required for road projects which extend transversely in the view (Landscape Institute, 2011). To avoid distortion of distance perception, the vertical field of view was kept at 27°, which is close to that of a standard lens. The resulted aspect of the captured views was 3:1.

The captured views were rendered into video scenes with the animations of moving traffic. Each video scene was 20 seconds long. The scenes of baseline scenarios, where there was no moving traffic, were still images and each lasted 10 seconds. In total, 36 video scenes and 6 image scenes were produced, and were merged in a random order to create a single long video, with the scene number (Scene 1 to Scene 42) appearing for 3 seconds before each scene and a 3-second blank interval after each scene. Another long video was made with scenes in reversed order. The two videos would be equally but randomly assigned to the participant sessions to reduce the possible effect of scene order.

Table 1. Parameters of the traffic conditions and noise levels (dB L_{Aeq, 18h}) at receiver positions.

| Noise emission level (dB L _{A10}) | HGV % | Traffic condition | | | | Noise level at receiver position | | |
|---|-------|-------------------|-------------|---------------------|---------------------|----------------------------------|-------|-------|
| | | Average speed | hourly flow | No. of cars in 20 s | No. of HGVs in 20 s | 100m | 200m | 300m |
| 79.0 | 10 | 100km/h | 2046 | 10 | 1 | 65.4 | 60.8 | 58.4 |
| 79.0 | 20 | 100km/h | 1533 | 7 | 2 | 65.4 | 60.8 | 58.4 |
| 83.3 | 10 | 100km/h | 5464 | 27 | 3 | 69.6* | 65.1 | 62.7 |
| 83.3 | 20 | 100km/h | 4131 | 18 | 5 | 69.6* | 65.1 | 62.7 |
| 87.6 | 10 | 100km/h | 14500 | 79 | 8 | 73.9* | 69.3* | 66.9* |
| 87.6 | 20 | 100km/h | 10928 | 49 | 12 | 73.9* | 69.3* | 66.9* |

* produced using the recording sample from 230 m, otherwise from 350 m

2.3. Preparation of audio stimuli

Audio recordings of the M1 traffic noise was made on site using a digital recorder Sound Devices 722 and a pair of DPA 4060 Miniature Omnidirectional Microphones,

worn by an operator facing perpendicularly to the road from distances of about 230 m and 350 m, each for 10 minutes long. Recordings from shorter distances were not available due to limited accessibility. The traffic flow was generally consistent during the recordings at speeds around 80-110 km/h as estimated based on the simultaneous video recordings. The weather on that day was dry and the wind speed was very low at about 2.2 m/s.

A 20-second sample was extracted from each of the two full audio recordings for audio reproduction. The recording sample was calibrated with the signal of a 01dB Cal01 Calibrator (94 dB/1 kHz) using a Neumann KU 100 dummy head and the playback system (see Section 2.4) that would be used for the experiment. The obtained sound equivalent level of the 20-second sample from 230 m was 70.4 dB(A), and that from 350 m was 63.1 dB(A).

The required noise levels at receiver positions in each scenario were calculated in CadnaA, and are shown in Table 1. In CadnaA, 3D models of the landscapes were built using the same input data as used for the 3D modelling in 3ds Max. The absorption coefficient of the ground, which was grassland in this study, was set as 0.5. The UK CRTN model was used to calculate the noise levels with input of the designed traffic conditions. The obtained $L_{A10,18h}$ levels were further converted to $L_{Aeq,18h}$ levels (Abbott & Nelson, 2002). Calculated levels for each scenario are shown in Table 1.

To produce audio files for received traffic noise in each scenario, the recording samples from 230 m and 350 m were edited in Adobe Audition CS6, either by increasing or by decreasing the overall levels. Audio files for scenarios marked with “*” in Table 1 were produced using the recording sample from 230 m, while the others from 350 m. The same audio files were used for the two HGV percentage scenarios to better serve the purpose of testing the visual effect of traffic composition while controlling the audio stimuli. This was supported by that changes in spectral character caused by changes in traffic composition were not remarkable in traffic conditions and at receiver distances used in this study, as the spectral shapes did not change dramatically over time within the original 10 minutes recordings, despite some changes in traffic composition during the time (Figure 2)

For baseline scenarios where there would be no traffic noise, bird sound was added to the soundtrack, since bird sound was the main background sound at the case site during recording and was also contained in the extracted traffic noise recording sample. An audio signal of pure bird sound was recorded in a quiet park in Sheffield and edited for use.

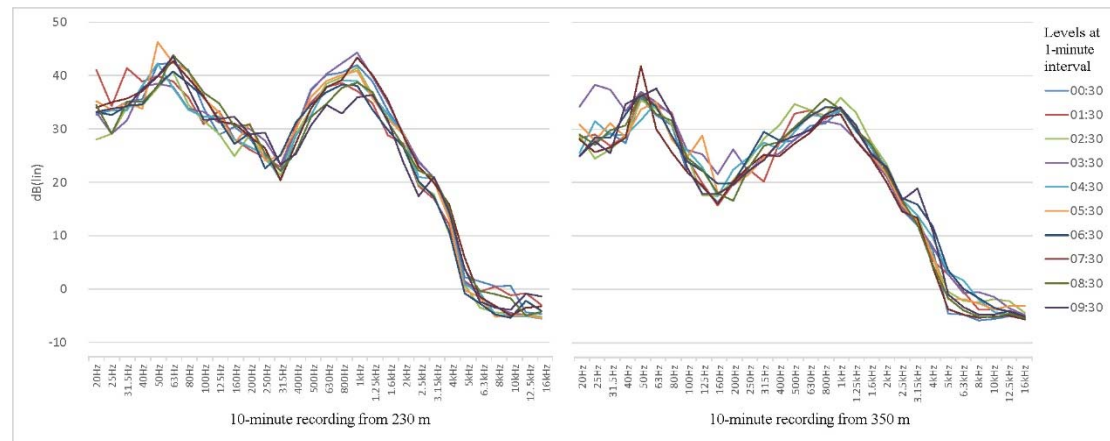


Figure 2. Changes of spectral shapes of the 10-minute recordings over time.

2.4. The experiment and procedure

Thirty university students (15 males and 15 females), aged 18-27 (Avg. = 21.1, S.D. = 2.1), with normal hearing and normal or adjusted to normal vision, participated in the experiment. The sample was more representative of younger population. Each participant session took about 20 minutes and the participant received five pounds as compensation for his/her time.

The experiment was carried out in a 3.5m × 3.5m × 2.3m anechoic chamber. The videos were played by an ASUS X550C laptop and projected via a Hitachi ED-X33 LCD projector onto a 203 cm × 152 cm screen 2.2 m away from where the participants were seated. Sound was presented to participants via a pair of Beyerdynamic DT 770 Pro headphones.

During the experiment, participants were asked to rate the overall pleasantness of each scene using visual analogue scale, that is, by marking a “x” on a bar which was 100mm long on the printed questionnaire and had only “low pleasantness” and “high pleasantness” labelled at the two ends. Before start, participants were told that the term overall pleasantness in this study concerned mainly visual pleasantness and sound pleasantness, but the purpose of this study was not mentioned.

2.5. Data analysis

Overall pleasantness of each scene was measured on questionnaires as the length from the low-pleasantness end of the visual analogue scale bar to the marked “x” on the bar in millimetre. For example, if the length is 70 mm, then the overall pleasantness score is 70. So possible overall pleasantness scores would range from 0 to 100. The perceived integrated impact in each scene with motorway was calculated by subtracting the overall pleasantness score of the scene from overall pleasantness score of the corresponding baseline scene without motorway. Possible integrated impact would thus range from -100 to 100, where a negative value means the motorway enhances the overall pleasantness whereas a positive value means the motorway

decreases the overall pleasantness, the larger the absolute value the higher the level of impact.

Within-subject ANOVA was run to analyse the effects of tested factors on the integrated impact, and regression analysis was carried out to explore the indicativeness of noise exposure to the impact. All statistical analysis was performed using IBM SPSS Statistics 21.

3. Results and discussion

3.1. The effects of traffic condition, distance to road and background landscape

A $3 \times 2 \times 3 \times 2$ within subject ANOVA was carried to analyse the effects of noise emission level, percentage of HGV, distance to road and background landscape on the perceived integrated impact of visual intrusion and noise of motorways. Table 2 shows the results. All the factors had significant effect on the perceived impact except percentage of HGV. The values of partial eta squared indicate that noise emission level was the most influential factor, followed by distance to road and then by background landscape. Marginal mean comparisons show that there were highly significant differences between each of the three noise emission levels and between distances of 100 m and 200 m ($p < .001$). Less significant difference was found between distances of 200 m and 300 m ($p = .031$). Significant interaction effects were found between noise emission level and Percentage of HGV, between noise emission level and distance to road, and between background landscape and distance to road, all with a medium effect size.

Table 2. Results of the ANOVA on the effects of noise emission level, percentage of HGV, distance to road and background landscape on the perceived integrated impact (only significant interaction effects are shown).

| Factor | f | df | p | η^2_p |
|---|---------|---------------|------|------------|
| Noise emission level* | 120.886 | 1,557, 45.141 | .000 | .807 |
| Percentage of HGV | 1.280 | 1, 29 | .267 | .042 |
| Distance to road | 58.926 | 2, 58 | .000 | .670 |
| Background landscape | 16.325 | 1, 29 | .000 | .360 |
| Noise emission level \times Percentage of HGV | 3.974 | 2, 58 | .024 | .121 |
| Noise emission level \times Distance to road | 5.143 | 4, 116 | .001 | .151 |
| Background landscape \times Distance to road* | 4.416 | 1,649, 47.810 | .016 | .132 |

*assumption of sphericity was violated and Greenhouse-Geisser correction was applied.

Although noise emission level and distance to road being the two most influential factors does not necessarily mean that noise impact was more dominant, since these two factors can also be decisive on visual impact, it does imply that noise level at

receiver position can be a potential indicator for the integrated impact. The significant effect of background landscape, as well as the significant interactions with background landscape and percentage of HGV, suggests that some weightings by visual factors might be needed.

Figure 3 plots the mean differences and the interactions. It can be seen in Figure 3-a that there is a steady increase in integrated impact by noise emission level. Percentage of HGV does change the increase rate, but the change is not remarkable, despite the interaction being reported as significant. Figure 3-b shows that integrated impact decreases by distance to road in a rapid-to-gentle pattern, which resembles the decrease in noise levels at receiver positions by distance. The pattern is most obvious with the highest noise emission level. Similar decreasing patterns are also found in visual impact in Jiang & Kang (2016) in the with-sound condition while less clear in the without-sound condition. These findings indicate the importance of noise level in deciding the perceived integrated impact. Figure 3-c shows that integrated impact is consistently higher in natural landscape than in residential landscape, which is of the same trend found with visual impact in Jiang & Kang (2016), and can also be related to the higher sensitivity to noise in more vegetated settings (Anderson et al. 1984; Mulligan et al. 1987). Another difference between the two background landscapes is the patterns of decrease of integrated impact by distance. The decreasing rate is relatively constant in residential landscape while changes dramatically in natural landscape. It should be noted, however, that the natural and residential landscapes in this study were both in a rural setting, and the results may not necessarily apply to urban settings.

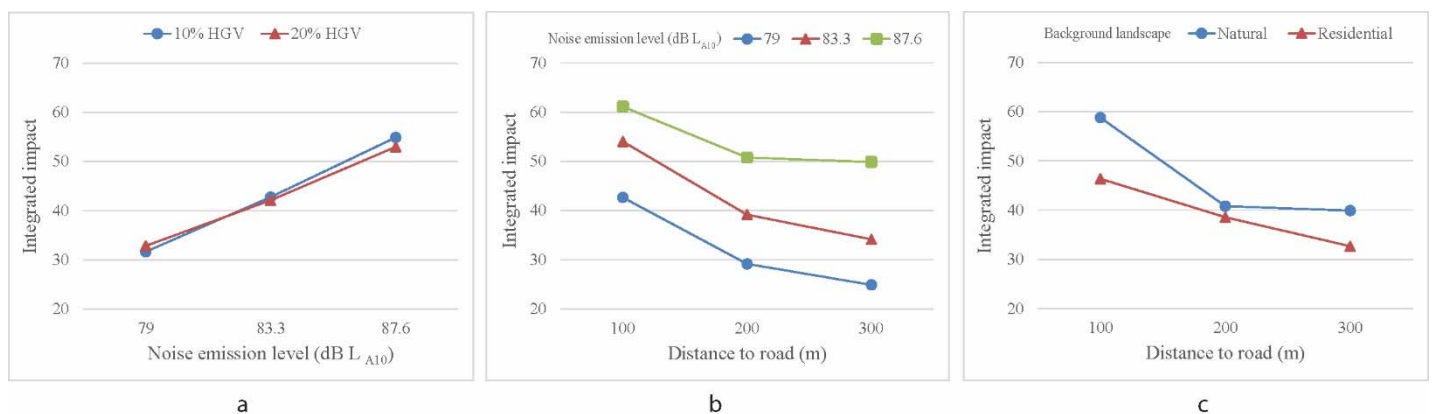


Figure 3. Perceived integrated impact of visual intrusion and noise of motorways: a. noise emission level vs percentage of HGV; b. distance to road vs noise emission level; c. distance to road vs background landscape.

3.2. Noise exposure as an indicator for the perceived integrated impact

Regression analysis, using noise emission level, distance to road, noise level at receiver position (noise exposure measure), background landscape (dummy coded) and percentage of HGV as independent variables and perceived integrated impact as

dependent variable, was carried out to explore if noise exposure can be a powerful indicator for the perceived integrated impact. Table 3 lists the tested models. It can be seen that noise level at receiver position is the most powerful predictor. This is congruent with the result in Section 3.1 that noise emission level and distance to road were the two most influential factors. Adding background landscape as a second predictor can slightly increase the prediction power of the model, which reflects the significant landscape effect found in Section 3.1. Adding other predictors cannot improve the model further due to collinearity or ineffectiveness of the factor. These results suggest that noise exposure weighted by landscape character can be developed into a potential indicator for the perceived integrated impact.

Table 3. Tested regression models

| Model | Predictors | R ² | Adjusted R ² | Std. Error of the Estimate | Note |
|----------------|---|----------------|-------------------------|----------------------------|--|
| Model 1 | Noise level at receiver position | .229 | .229 | 20.635 | Only one independent variable included in analysis |
| Model 2 | Noise level at receiver position, background landscape | .253 | .252 | 20.319 | All independent variables included in analysis, stepwise entry |
| Model 3 | Noise level at receiver position, background landscape, noise emission level, percentage of HGV, Distance to road | .255 | .252 | 20.319 | All independent variables included in analysis, forced entry |

Table 4 shows the details of Model 2 which uses noise level at receiver position and background landscape as predictors. In the model, every one dB(A) increase in noise level at receiver position will lead to 2.490 increase in perceived integrated impact on the scale used in this study, and being in residential landscape decreases the impact by 7.298 as compared to being in natural landscape. However, it should be noted that the prediction power of the model is low, with an adjusted R² only equal to 0.252, which means noise level at receiver position and background landscape together can only explain 25.2% of the variation in perceived integrated impact, the majority of the variation was decided by factors that were not tested in this study. Similar low predictiveness is also found of noise exposure for noise annoyance in literature. By reviewing 39 social surveys Job (1988) concluded that only typically less than 20% of the variation in noise annoyance could be explained by noise exposure, while factors such as attitude to the noise source and sensitivity to noise could account for larger

variation in noise annoyance. This might also be applied in the case of integrated impact of visual intrusion and noise, that individual attitude to the intrusion sources and sensitivity to the intrusions can play a more important role in deciding the level of perceived impact.

Although factors such as ecological validity, variable control and experimenter effect may alter the cause-effect relationships found in laboratory experiments as compared to those exist in real life situations (McLeod, 2012), results of the experiment in this study indicate that prediction power of objective exposure measures for the perceived integrated impact is low, which suggests that while using noise exposure as an indicator can conveniently allow an preliminary understanding of the climate of the integrated impact, it may not be sufficient to guide evidence-based decision makings regarding noise and visual impacts of motorways. Character of the affected population should also be studied for the assessment.

Table 4. Regression coefficients of Model 2 (adj $R^2 = 0.252$).

| | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. | Partial R^2 |
|---|-----------------------------|------------|---------------------------|---------|------|---------------|
| | B | Std. Error | Beta | | | |
| (Constant) | -117.323 | 9.050 | | -12.964 | .000 | |
| Noise level at receiver position (dB(A)) | 2.490 | .137 | .479 | 18.187 | .000 | .485 |
| Background landscape (dummy coded as: natural = 0; residential = 1) | -7.298 | 1.237 | -.155 | -5.902 | .000 | -.177 |

Dependent variable: perceived integrated impact

4. Conclusions

This study aimed to investigate the effects of traffic condition, distance to road and background landscape on the perceived integrated impact of visual intrusion and noise of motorways, and explore if noise exposure can be a powerful indicator for the perceived integrated impact. A laboratory experiment, using computer-visualised scenes with edited audio recordings to present six traffic conditions consisting of three levels of noise emission and two levels of percentage of HGV, three distances to road and two types of background landscape, was carried out and human responses to the scenes were obtained.

The results show that traffic condition was the most influential factor. Specifically, it was the traffic volume as expressed by noise emission level that strongly influenced the perceived integrated impact while traffic composition did not make noticeable differences. Distance to road was the second most influential factor, followed by background landscape. Generally, perceived integrated impact increased steadily by noise emission level, decreased in a rapid-to-gentle pattern by distance to road, and was consistently higher in natural landscape than in residential landscape.

Noise level at receiver position was the most powerful predictor of the perceived integrated impact among the factors tested in this study. Adding background landscape as a second predictor can further increase the prediction power of the regression model which however is still relatively low ($\text{adj } R^2 = 0.252$). A larger part of the variation in the impact might be explained by factors such as individual attitude to motorways and sensitivity to visual intrusion and noise. The results suggest that noise exposure at the receiver weighted by character of background landscape can be used as an indicator for a preliminary understanding of the climate of the integrated impact.

With further studies that involve larger samples and cover wider ranges of predictor variables, as well as studies that address issues of receiver characters, more powerful prediction models for the perceived integrated impact can be obtained, and together with current advances in noise and visual impact mappings, possible tools to map the perceived integrated impact can be developed and applied to assist environmental impact assessment of motorways.

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