Noise impact assessments in early stage road and railway planning

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ABSTRACT

During early route planning of a new road or railway, several potential routes are considered and evaluated. The route selection assessment, also referred to as optioneering, requires input from various specialists to evaluate strengths and weaknesses of a potential route. The assessment is associated with many constraints, such as construction costs, geometric design, visual amenity and environmental effects. Noise impact assessments, however, are challenging to take into account at such an early stage due to time consuming modelling and calculation procedures that depend on a predefined route. In this study, a new and simplified noise impact assessment procedure, based on the reciprocity principle, is presented. By placing point sources on dwellings and receivers in a grid over the area of interest, the resulting noise map displays the potential noise impact of all grid points. A pathfinding algorithm that traverse the quietest points in the map determines the optimal route with minimal noise impact. Furthermore, as it does not depend on a predefined route, it is a flexible and useful tool for prioritizing multiple routes during early planning stages. A case-study is presented and a comparison between the proposed procedure and the common noise impact assessment is carried out and discussed.

Keywords: Noise impact assessment, noise modelling, route optimization

I-INCE Classification of Subjects Number(s): 52.1, 52.9

1. INTRODUCTION

The planning of a new road or railway is a complex process driven by a specific political agenda, such as reducing travel time, relieving congestion, or connecting a new area to the existing road or railway network. In early planning stages, a large number of route alternatives and constraints from various engineering disciplines are considered and evaluated (1). In an iterative process, the number of route alternatives is narrowed down to a few that is evaluated in depth. For some constraints, e.g., geometric design, the cost implication can be determined quite precisely whereas others such as environmental impacts are more difficult to evaluate (1,2). Due to the qualitative nature of environmental factors, an environmental impacts assessment (EIA) is difficult to carry out in early planning stages where many potential routes are still in play (3). The noise impact assessment, however, which is often a part of the EIA, can assign a quantitative measure (typically the number of noise exposed dwellings) to each potential route. However, the time-consuming calculation procedure of noise impacts assessments makes it impractical to use noise calculation software in the early planning stages. Alternative methods have been proposed (2,3,4), however, these are based on evaluating existing alignments, whereas this study is also concerned with generating optimal alignments.

In the following, a methodology for simplified noise impact assessments is given, that can be incorporated into early planning stages of route selection. A fictitious case study is then presented and an optimal route is calculated based on the proposed methodology. The calculated optimal routes and two hand-drawn paths are evaluated and compared using the proposed methodology and commercial noise modelling software.

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2. METHODOLOGY

Based on the assumption, that a new road or railway can be approximated by a combination of point sources in an equi-distant grid, placed in the area of interest. The use of this method is two-fold: Firstly, by assigning each grid point a sound power and calculating the noise exposure on nearby dwellings, the total contribution from all grid points will generate a map of weighted points from which an optimal route, that minimizes the noise exposure on dwellings, can be calculated. Secondly, in later stages, where a limited number of routes have been selected, the method can be used to prioritize these routes by selecting grid points closest to each individual route and evaluating the noise exposure by the grid point values. In the following, these two methods are described in detail.

2.1 Weighted noise map

An optimal route for a new road or railway should, from an acousticians perspective, avoid noise sensitive areas and minimize the number of dwellings with high noise exposure, thus minimizing noise induced health problems as well as costs of noise mitigation measures. Whereas other engineering disciplines are equally important for the determination of an optimal route, the present study is solely concerned with minimizing the number of dwellings with high noise exposure. That being said, the optimal path should also by reasonably short and have relatively smooth curvatures.

The weighted noise map is a geospatial representation of grid point values, in which noise sensitive areas are visible. The grid point value represents a summation of noise levels induced by that particular point on nearby dwellings if a route were constructed using that grid point. Grid points with highest weights will contribute more to the noise exposure on dwellings and should be avoided. Contrarily, grid points with lowest weight can be combined to yield an optimal route with minimized noise exposure.

To find an optimal path, a pathfinding algorithm called the A* algorithm (5), is used. Several other alternatives exists (6), however this particular algorithm has shown promising results in preliminary tests. As input parameters, the A* algorithm takes a weighted graph, start and end points, and a heuristic function. The graph consists of nodes and edges. Nodes represent the equi-distant grid points and edges, the lines connecting nodes, represent the cost of going from a particular node to an adjacent node. Specifically, the algorithm chooses a path that minimizes a cost function \( f = g + h \) at each node, that is comprised of an edge cost, \( g \), the grid point weights, and a step cost, \( h \), a geometric distance factor between grid points, i.e., a heuristic function. The graph is constructed iteratively by adding nodes for each grid point and edges to adjacent nodes with associated weights. In this process, the allowed direction of movement of the algorithm, from one node on to another, is set.

In an equi-distant grid, there are at least four directions of movement: up, down, left, and right, each with the same step cost, \( h_s \). Additionally, diagonal movement between nodes can be allowed with a step cost \( h_d = \sqrt{2} \cdot h_s \). To obtain useful paths from the algorithm, proper scaling of edge and step costs is important. If the step cost is much more expensive than the edge cost, the algorithm will ignore the values of the noise map and simply find the shortest path. On the other hand, if the edge cost is more expensive than the step cost, the algorithm might find a path that is too long or too curved. The scaling is problem-specific and requires some manual adjustments. Another option is to only allow movement in four directions and set the step cost \( h_s = 0 \), thus putting emphasis on the edge cost alone.

The weighted noise map can easily be constructed and calculated with common outdoor noise modelling software. By use of the reciprocity principle, i.e., sources and receivers may be interchanged and the same waveform will be observed, point sources are placed on dwelling façades and receivers in an equi-distant grid. The total noise level at a given grid point is a summed contribution of nearby point sources situated on dwellings. This technique does have limitations. For instance, the reciprocity principle is only valid for simple meteorological conditions and does not consider wind directions. However, the level of detail calculated is suitable for the early planning stages or could be used, for example, for a worst-case assessment with strong prevailing winds.

2.2 Evaluation of route alignments

During the route alignment process, the number of potential routes decreases, as the alignment corridor gets narrower. During this phase but before the EIA can commence, the noise impact evaluation of selected routes can be of interest. In this phase, small changes to the alignments can
happen frequently, and the proposed method can evaluate each change and compare to a reference. Using the weighted noise map, a proposed alignment is approximated by selecting grid points closest to it. By comparing statistical properties of selected grid point weights, the proposed alignments can be evaluated and ranked.

3. CASE-STUDY RESULTS

A fictitious case-study was carried out to investigate the capabilities of the proposed method. A large rectangular area of 16 km by 27 km, situated in the western part of Denmark, was chosen as study area. The area is mainly agricultural land with scattered villages and a few cities with populations ranging from 5000 to 20000. Using SoundPLAN, a commercial outdoor sound modelling software, a digital terrain model was generated and dwellings imported. On each dwelling façade, a point source was placed with a flat frequency spectrum (100 dB per 1/3 octave band), i.e., white noise with an overall sound power level of $L_w = 114$ dB(A). Other noise spectra, e.g., that of road traffic noise or railway noise, could equally be used. A total of 190000 point sources on 50000 dwellings were generated. With a grid point spacing of 50 m, a calculation of the noise levels at 180000 receivers were conducted. The calculation of the weighted noise map took about 48 hours.

The geographical region is shown in Figure 1 with the weighted noise map as a transparent overlay (dark colors correspond to high noise levels). Areas of high noise exposure agrees well with the general dwelling density, as would be expected. A fictitious scenario in which two parts of the area needed a new route, be it a road or railway, led to a start point in the southeastern part of the map and an end point in the northwestern part.

The proposed method was used to calculate several optimal paths generated by the A* algorithm by varying the input parameters. The paths were then compared and ranked. Furthermore, two fictitious route alignments, drawn by hand through the area in question, were evaluated using the weighted noise map and compared with the paths generated by the A* algorithm. Lastly, an ordinary noise impact assessment was carried out using the two hand-drawn route alignments and two of the optimal paths. The paths were assigned sound power characteristics of road traffic noise. Counting the number of dwellings exposed to sound levels exceeding the day-evening-night level, $L_{den} = 58$ dB(A), commonly used as recommended noise limit in Danish road projects, was used to compare the four route alignments.
3.1 Optimal routes

The A* algorithm was used to generate optimal paths. The algorithm generates a minimum cost path by traversing a graph. To evaluate the capabilities of the algorithm, three graphs, summarized in Table 1, were constructed.

![Image of weighted noise map](image)

Furthermore, calculations were performed using the weighted noise map as edge costs, $g$, and two different step costs, $h$, calculated using the following formula,

$$h = \begin{cases} 
\mu \cdot \text{mean}(g) & \text{, square movement} \\
\sqrt{2} \cdot \mu \cdot \text{mean}(g) & \text{, diagonal movement}
\end{cases}$$

(1)
where $\mu$ is a scaling factor. The values of $\mu$ were chosen based on preliminary tests.

In Figure 2, the result of calculating paths based on the three graphs, G1, G2, and G3, with and without step costs (a total of 6 paths), is shown.

![Figure 2](image)

**Figure 2** – Optimal paths calculated with the A* algorithm.

Path 1, 2, and 3 (calculated without step costs, $\mu = 0$) are shown in black, blue, and green color, respectively. Path 4, 5, and 6 (calculated with step costs, $\mu = 0.1$) are shown in dashed line style in black, blue, and green color, respectively.

The six paths illustrate how the step cost $h$ and constraints on the algorithms' freedom to move in various directions affect the resulting route. Path 2 especially, that were given freedom to move in 8 directions, takes a large detour due to the zero step cost. Path 3 takes a straighter route, going round the right side of the city in the central part of the map because it was limited to three direction of movement. Path 4 and 6 are more or less similar to Path 1 and 3 suggesting that these paths, which have different step costs, are close to optimal in terms of both length and noise exposure. Path 5, however, changes greatly by the added step cost, showing that Path 2 was sub-optimal in terms of length.

The six paths are compared in terms of length and noise exposure in Table 2. To summarize and quantify the noise exposure of each path, the cumulative distribution function (CDF) of grid point
weights, which intersects with a given path, was calculated.²

To achieve a single value that can be used to rank the six paths, the 90\textsuperscript{th} percentile of the CDF of grid point weights, dubbed path score, were used. With a probability of 90\%, the grid point weights take values less than or equal to the 90\textsuperscript{th} percentile (shown in the right-most column in Table 2). The CDFs are shown in Figure 3 (lower path score is better).

Table 2 – Optimal path attributes.

<table>
<thead>
<tr>
<th>Path</th>
<th>μ</th>
<th>Length [km]</th>
<th>Path score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>29.0</td>
<td>82</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>33.5</td>
<td>81</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>21.0</td>
<td>85</td>
</tr>
<tr>
<td>4</td>
<td>0.1</td>
<td>26.3</td>
<td>83</td>
</tr>
<tr>
<td>5</td>
<td>0.1</td>
<td>27.5</td>
<td>83</td>
</tr>
<tr>
<td>6</td>
<td>0.1</td>
<td>21.0</td>
<td>86</td>
</tr>
</tbody>
</table>

Figure 3: Cumulative distribution functions of calculated optimal paths.

The path score for Path 2 is 81 and the CDF, shown in blue in Figure 3, is the left-most line. This shows, that the grid point weights, Path 2 traverses, statistically has more low value points than any other path. Figure 3 illustrates that constraints, in terms of step costs and direction of movement, shift the CDFs to the right, to higher cumulative noise exposure. The length of Path 2 is also the longest of all paths. This is also seen in Table 2, where the path score for Path 4, 5, and 6 are higher than their equivalent paths without step costs.

3.2 Evaluation of route alignments

From the above-presented case study, an optimal path with minimal noise impact can be found without a predefined alignment. In other cases, where one or several alignments have been proposed, the weighted noise map can be used to make a quick assessment of their noise impact. This assessment is no replacement for a thorough noise impact assessment but in early planning stages, the weighted noise map method opens for the possibility of influencing the final route alignment towards a situation

³ The grid point weights is a logarithmic scale related to the decibel-scale, however, to ensure that it is not interpreted as actual sound levels, the term weights is used.
where fewer people are exposed to noise.

Two route alignments, A1 and A2 (shown in Figure 4), were drawn by hand and evaluated using the weighted noise map. The two alignments were then compared to Path 1 and 6, presented in the previous section. Path 1 and 6 (also shown in Figure 4) were slightly altered by smoothing the original paths to obtain profiles that are more realistic. Path 1 shows some unusual curves that is not entirely realistic for a road nor railway; however, for evaluating the noise impact in this fictitious case-study, it is sufficient.

The 90th percentiles of the CDFs were used once again to compare the noise impact between routes. A summary of the paths is given in Table 3 and the CDFs are shown in Figure 5.

![Figure 4: Route alignments A1 and A2 (in red and magenta respectively) and smooth versions of Path 1 and 6 (in black and dashed green respectively).](image)

From the CDFs and path scores, it is seen that the two hand-drawn alignments, A1 and A2, has a higher noise impact than the optimal paths calculated with the A* algorithm.

To get a more precise comparison between these four paths, an ordinary noise impact assessment was carried out. The paths, summarized in Table 3, were imported into SoundPLAN as roads and the day-evening-night level, Lden, was calculated for dwelling façades within 250 m of the alignment. Furthermore, dwellings closer than 50 m of the road were deleted in order to obtain a more fair comparison. All roads were assigned the same attributes corresponding to a highway with an annual average daily traffic volume of 30,000 vehicles.
Table 3 – Path attributes.
Length and path score (90th percentile of grid point weights).

<table>
<thead>
<tr>
<th>Path</th>
<th>μ</th>
<th>Length [km]</th>
<th>Path score</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>-</td>
<td>21.9</td>
<td>88</td>
</tr>
<tr>
<td>A2</td>
<td>-</td>
<td>21.1</td>
<td>90</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>24.0</td>
<td>82</td>
</tr>
<tr>
<td>6</td>
<td>0.1</td>
<td>20.4</td>
<td>86</td>
</tr>
</tbody>
</table>

Figure 5: Cumulative distribution functions of alignments A1, A2, Path 1 and 6.

The calculation results were once again compared using the CDFs of the four paths, however, now with actual sound levels indicated by Lden. The results are shown in Figure 6. In general, the CDFs of the four paths are very similar. A1 is slightly shifted to the right, indicating a higher noise impact but from this representation of the results, it is not clear how much the paths differ. Thus, another measure, the histograms of sound levels were calculated and is shown in Figure 7. Here it becomes clearer, that the four paths differ substantially.

The number of affected dwellings is much smaller for the optimal paths, Path 1 and 6, than alignment A1 and A2. In addition, both A1 and A2 have more dwellings with higher sound levels.

The number of dwellings where façade levels exceed Lden = 58 dB(A) has been calculated and is summarized in Table 4.

The assessment of noise impact, of the four paths, using the weighted noise map method, was carried out using path scores. Comparing these scores, with the number of dwellings exposed to levels greater than Lden = 58 dB(A), suggests that there could be a relationship between the weighted noise map method and the ordinary noise impact assessment.
Figure 6: Cumulative distribution functions of sound levels, Lden, for alignments A1, A2, Path 1 and 6.

Figure 7: Number of receivers as function of level Lden.

Table 4 – Path comparison. Length and number of dwellings with Lden ≥ 58 dB(A).

<table>
<thead>
<tr>
<th>Path</th>
<th>μ</th>
<th>Length [km]</th>
<th>Path score (90th percentile)</th>
<th>Number of noise exposed dwellings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>24.0</td>
<td>82</td>
<td>85</td>
</tr>
<tr>
<td>6</td>
<td>0.1</td>
<td>20.4</td>
<td>86</td>
<td>97</td>
</tr>
<tr>
<td>A1</td>
<td>-</td>
<td>21.9</td>
<td>88</td>
<td>155</td>
</tr>
<tr>
<td>A2</td>
<td>-</td>
<td>21.1</td>
<td>90</td>
<td>194</td>
</tr>
</tbody>
</table>
4. DISCUSSION

The results presented above indicate that there exists a relationship between the number of dwellings exposed to sound levels exceeding $L_{den} = 58$ dB(A) and the path scores derived from the cumulative distribution functions of grid point weights. This main outcome of the proposed method is based on a fictitious case study that has some limitations.

First, the calculation of the weighted noise map is computational heavy, even for a rather large grid spacing of 50 m. With this spacing, the exact position of a particular grid point could make a big difference on the sound level generated at a dwelling. If the point is very close to the dwelling, it will generate a high sound level and vice versa. With a large number of dwellings and grid points this influence should be averaged out. However, further work is required to establish the significance of grid point density.

Second, the optimal paths were not entirely realistic, due to large gradients in bends and vertical alignments. Constraints on the curvature could possibly be built into a generic tool. In an iterative process, the A* algorithm could generate an optimal path that is smoothed and reevaluated using a finer meshed noise map, within a corridor determined by the initial path.

Third, the hand-drawn route alignments, that were introduced to imitate a more realistic scenario in which route alignments already existed, would have been constructed more carefully in the real world and possibly with more attention to the noise impact.

Fourth, the sound power used in the calculation of the weighted noise map, was chosen to be white noise and not a more realistic sound power source, such as road vehicle noise. Further research is needed in this area but it could potentially open up for a direct assessment of equivalent sound levels at dwellings instead of grid point weights.

5. CONCLUSIONS

A methodology for noise impact assessments in early route planning stages has been presented and examined in a case study. Based on a grid of point sources placed in the area of interest, a weighted noise map can be calculated which is used to generate and compare optimal route alignments. Furthermore, the weighted noise map can be used to evaluate the noise impact of existing alignments and rank them by noise impact using the cumulative distribution function. An ordinary noise impact assessment was carried out in a case study to compare route alignments with optimal paths calculated by the A* algorithm. It was found, that the optimal paths generated lower noise levels at dwellings and a fewer number of dwellings were exposed to noise levels exceeding $L_{den} = 58$ dB(A). A relationship between the 90th percentile of grid point weights and the number of noise-exposed dwellings does seem to exist but needs to be established through further research.

REFERENCES