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The influence of fan and traffic noise on speech intelligibility in Dutch traffic tunnels

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Abstract

Traffic tunnels are generally harsh acoustic environments. Materials used to cover walls, ceilings and road surface are not primarily selected on the basis of their acoustic qualities, but rather according to various safety-related criteria. As a result, long reverberation times are observed, which have an adverse effect on speech intelligibility. Nevertheless, in case of an emergency a public address system is used to reach the public inside a tunnel. When using such systems in the absence of noise, speech intelligibility usually complies with a generally accepted minimum standard (Speech Transmission Index STI>0.35). Two sources of noise reduce STI-values to unacceptably low values: noise due to moving traffic and noise produced by high-power fans (necessary to expel smoke from tunnels in case of fire). A computational procedure was developed, based on ray-tracing techniques, to predict the Speech Transmission Index. The resulting speech intelligibility predictions are found to be very useful in the design stage of public address systems for tunnels. This is illustrated by means of predictions for the newly built Benelux tunnel. By systematically varying several design parameters, and computing the effects on speech intelligibility, better design choices can be made.

1. Introduction

When new traffic tunnels are built in The Netherlands, much attention is given to various safety aspects. An important issue is the speed and efficiency with which sections of the tunnel may be evacuated in case of an emergency. The role of the public address system is crucial.

Unfortunately, it is not always easy to obtain acceptable speech intelligibility using a PA-system. There are several reasons for this. First of all, the geometric proportions of the tunnel, combined with the reflectivity of (tiled or concrete) walls and ceiling, lead to long reverberation times. The application of acoustically more absorbent materials is often not feasible in tunnels; the choice of materials tends to be determined by other criteria, such as fire resistance (inflammability, heat protection of the tunnel construction). The designer of PA-systems usually has to accept adverse reverberation conditions as a given.

In addition to the tunnel acoustics, the presence of noise sources limits speech intelligibility even further. Noise is not only produced by (moving) traffic, but also by large fans mounted against walls or ceilings. These fans are operated in emergency situations to expel smoke from the tunnel. Noise levels due to these fans at listener positions in the tunnel have been observed to range between 80 and 105 dB(A).
In new tunnels, the speech intelligibility of the PA system is required to meet certain minimum standards with regard to the speech intelligibility at various listener positions. These requirements are given in terms of the Speech Transmission Index (STI) [1]. Currently, the minimum requirement is STI>0.35 at all practical listeners positions under all conditions, including fan noise. The minimum STI-requirements will be raised for future tunnels, in compliance with the new standard (currently in draft) ISO 9921 [2].
For the last 15 years, new PA-systems in tunnels have been subjected to STI-measurements as a means of 'acceptance testing'. It is also desirable to predict speech intelligibility as part of the PA-system design process, *before* the actual tunnel is even built. To this end, a STI prediction procedure was implemented based on ray tracing. By comparing STI predictions with STI measurements in existing tunnels, this procedure was validated [3]. In this paper, we will show results of application of the prediction procedure to the (new) Benelux tunnel.

2. STI prediction procedure

Before calculating STI-predictions, all necessary input-data must be collected. This includes characteristics of the PA system: overall frequency transfer, directivity patterns and distortion of the loudspeakers, position of the loudspeakers in the tunnel, etc. Also, the characteristics of the tunnel (geometry) and surface materials (acoustic absorption and scattering) must be known. Finally, a description of the noise sources is needed (spectrum and directivity).
The calculation starts out by determining the (squared) impulse response due to the PA system at various listener positions. Except for the influence of ambient noise, the squared impulse response contains all the information necessary to calculate the STI value at a given position [4]. The impulse response is calculated by means of ray tracing, in our case using the commercial software package *Odeon* [5]. Since noise is an important determining factor in tunnels, the noise spectrum at the listener positions must be also calculated. This can be done using ray tracing techniques as well, although computationally less involved methods may also yield sufficient accuracy.
The calculation of the Speech Transmission Index is based on the Modulation Transfer Function (MTF) [4]. From the ray-tracing results the MTF is calculated, using Matlab® scripts. These scripts further calculate the final STI values based on the MTF and the noise data. The final result of using the prediction procedure is usually a set of predicted STI values at various positions in the tunnel, under several noise conditions.
Figure 1 shows the correlation between measured and predicted STI values for 154 measuring points, differing in tunnel geometry, surface materials, noise spectrum, loudspeaker type, loudspeaker position and listener position. Figure 1 shows that the procedure is effective in predicting STI values. This conclusion is supported by figure 2, which shows measured and predicted STI values (in a single condition without noise) for various positions in the same tunnel. The predictions of figures 1 and 2 were obtained without using a priori knowledge of measurement results for the corresponding conditions.

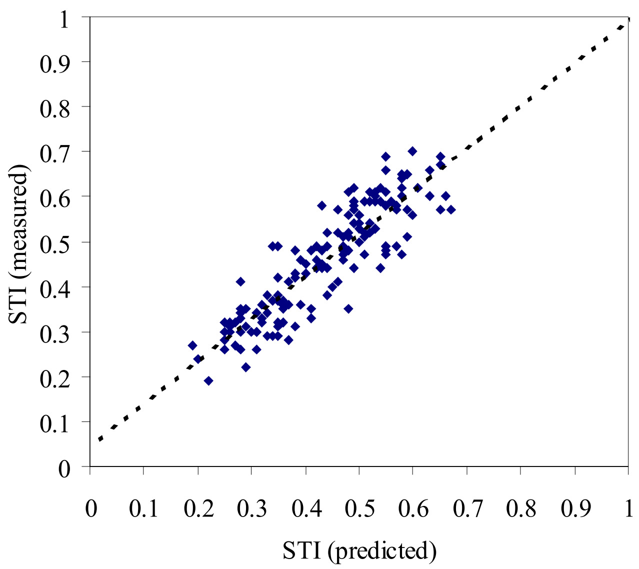

Figure 1. Correlation between predicted and measured STI values (correrelation coefficiënt r=0.89).

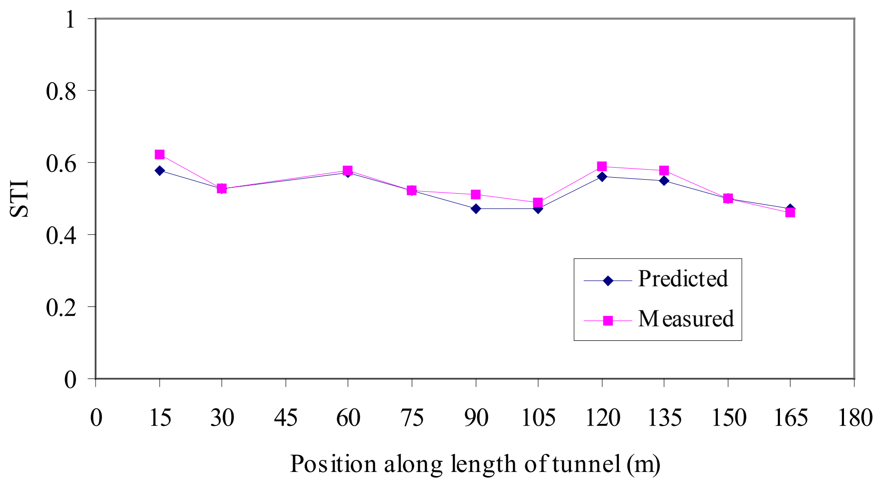

Figure 2. Measured and predicted STI values for several listener positions (indicated in meters along the length of the tunnel) for a condition without noise, at a height of 1.50 meter above the road surface.

3. Prediction results Benelux Tunnel

For the design of the PA-system in a new tunnel, the prediction procedure was used to find out which choices for several design parameters yield the highest speech intelligibility. These parameters included loudspeaker type, position of loudspeaker cluster relative to an operating fan (noise source), and distance between consecutive clusters (arrays) of loudspeakers.

Figure 3a shows a considerable difference between the loudspeaker types. Figures 3b and 3c show results for the middle loudspeaker type of figure 3a. Figure 3b shows a minor effect of the position of the loudspeaker clusters in relation to a single noise source. The distance between loudspeaker clusters (figure 3c) *is* an important variable; figure 3c shows that an increase of this distance leads to positions with reduced intelligibility.

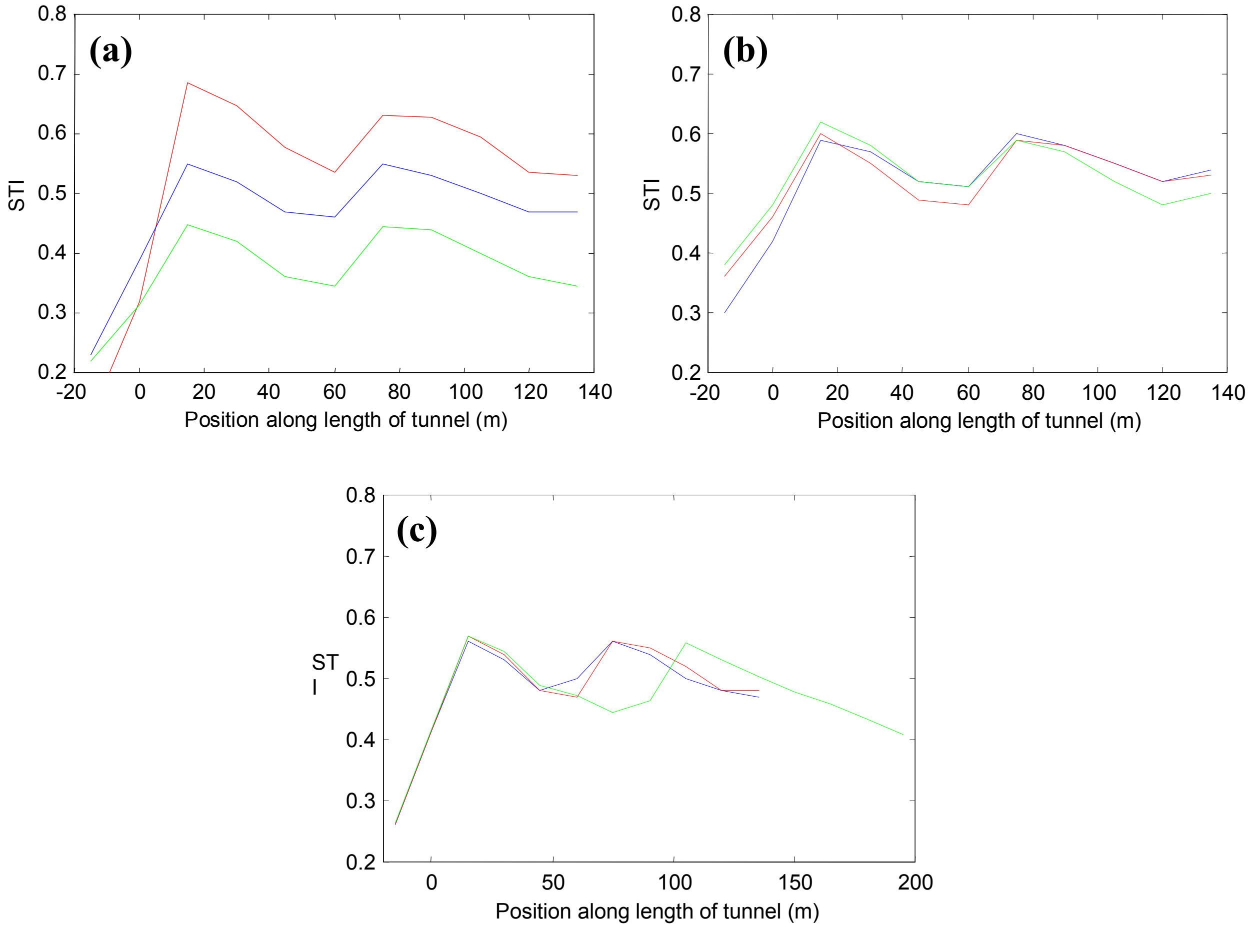

Figure 3. Predicted STI values: (a) for three different loudspeaker types in traffic noise, (b) in noise of a single fan at three different positions (0, 60 and 120 m), and (c) for three different distances between loudspeaker clusters (first cluster at 0 m, and second cluster respectively at 60, 68 and 90 m).

Conclusions

The procedure developed to predict speech intelligibility in tunnels yields STI predictions that correspond well with measurements carried out in existing tunnels. Application of the procedure on a new tunnel shows that the procedure enables PA-system designers to quantify the effects of loudspeaker type, loudspeaker position relative to noise sources, and distance between loudspeaker clusters on speech intelligibility. It is fair to assume that the influence of other design parameters may be predicted equally well.

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