A Traffic Assignment Model To Reduce Noise Annoyance in Urban Networks

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The possibilities of reducing traffic noise annoyance in urban networks without reducing the total amount of automobile traffic are investigated. The basic idea is to reduce noise levels by influencing drivers' route choice. Possibilities to influence this choice were investigated by modifying an equilibrium assignment algorithm.

In the past few decades noise annoyance has become an increasing problem, especially in the Netherlands with its dense population. Therefore a law has come into force, *Wet Geluidhinder,* that specifies permissible noise levels under various circumstances. This study concerns road traffic *(1).* Investigations have shown that the noise annoyance problem is most severe within towns, which restricts the possibilities for traffic engineers to solve the problem: noise barriers cannot be applied in the inner cities, for instance.

This study seeks to determine whether modified route choice might help to solve the noise problem. On roads with few houses, or with few houses close to the road, traffic flow should be increased in order to reduce the flow on roads where noise annoyance occurs or can be expected. Thus a comprehensive rather than an ad hoc approach is provided. This study involves unmodified fixed travel demand and an unmodified travel mode choice and is restricted to motor traffic.

Because the noise level is a logarithmic function of the flow, it is expected that the best solution will be created when most traffic is concentrated on a small number of main routes. However, it is also possible that a concentration of traffic on several routes combined with a diversion of oversaturated flows to low-density roads will be a feasible solution as well. The model to be discussed appears to support this hypothesis.

HOW TO MEASURE TRAFFIC NOISE

Noise can be quantified objectively in various ways:

- Noise level (in decibels)
- Loudness (in sones)
- Loudness level (in phons)
- Frequency characteristics (in Hertz)
- Interval time (in seconds)

Noise level is the most instructive, especially when it is A-weighted. This means that the measures are adapted to the way humans observe different frequencies.

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In the Netherlands the equivalent noise level (L_{eq}) in A-weighted decibels is the most commonly applied measure. It smooths a fluctuating noise as follows:

$$L_{eq} = 10 \log \left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{p^2_{\text{eff}}}{p_0^2} \, dt \right) \tag{1}$$

where

p_{eff} = effective sound pressure,
p_0 = reference pressure,
$t_2 - t_1$ = observed time interval, and
L_{eq} = duration-sensitive noise level.

It should be pointed out, however, that such a noise level gives less representative values for nighttime traffic, when isolated cars pass by, than in steady flows.

Basically, traffic noise is a function of flow, traffic composition and speed, and the distance between the facade of the houses and the heart of the road (hereafter called the facade distance). In accordance with the current legal standards, trucks are subdivided into medium-heavy and heavy traffic according to certain criteria. Buses belong to the heavy-traffic category.

Unlike noise levels, noise annoyance is subjective. All kinds of personal characteristics influence a person's sense of annoyance. Nevertheless, investigations have shown a remarkable correspondence when the number of strongly annoyed persons is determined as a function of noise level.

An inquiry in Amsterdam resulted in the following relationship:

$$\text{Percentage of strongly annoyed persons} = 0.0038 * \exp(0.1143 * L_{eq}) \tag{2}$$

This means that a doubling of the traffic flow resulting in a 3-dB(A) increase of the noise level causes a 40 percent increase in the number of strongly annoyed people.

HOW TO MODEL THE NOISE PROBLEM

Background of the Problem

The model assumes the existence of an origin-destination (O-D) table for motor traffic, which means that it concentrates on route choice and assignment. Within optimization problems, a distinction can be made between user-optimizing and system-optimizing theories. Wardrop *(2–4)* formulated these two principles as follows:

1. Travel costs on all the routes actually used are equal, and less than those that would be experienced by a single vehicle on any unused route, and
2. At equilibrium, the average journey cost is minimal.

These two optimums do not usually coincide.

Although the system equilibrium creates the most efficient traffic pattern for the community, it should be observed that it is an idealized target that will not be observed in practice without some form of enforcement.

Beckmann et al. *(5)* proved that this is equivalent to a convex minimization problem. Using the network concept proposed by Florian *(6)*, this can be written as

$$\min Z = \sum_a \int_0^{f_a} c_a(x)\, dx \tag{3}$$

where

Z = objective function,
f_a = flow on link a, and
c_a = average travel cost function for link a (in this paper a travel-time function).

Furthermore, the objective function Z should meet such conditions as positiveness, monotonous increase, and convexity to guarantee the existence of a solution and to warrant that it is unique and stable.

Regarding these conditions and given the background of the two different optimization approaches, one should realize that

1. Although a system optimization would seem the obvious way to reduce noise levels and noise annoyance within a town, such a solution is too unrealistic to be practicable. At best it gives an idea of the most favorable situation that can be reached.
2. The logarithmic noise-level and noise-annoyance functions do not meet the above conditions, which are necessary for applying the existing optimization techniques.

Extension of the Set of Constraints

The arguments mentioned in the previous section led to the choice of the following approach: a user minimization of the travel time with the addition of an extra condition. This condition, giving the maximum flow X on a road as a function of facade distance, traffic composition and speed, and the noise standards to be met, is not a constraint in the traditional sense, because it is incorporated in the link travel-time functions as follows:

$$\begin{aligned} C^* &= X \quad \text{for } X < C \\ &= C \quad \text{for } X > C \end{aligned} \tag{4}$$

where

C = link capacity in traffic theory,
C^* = capacity to be used in the link travel-time function, and
X = calculated maximum flow.

This results in an unmodified travel-time function for $X > C$ and a compressed function for $X < C$.

As a consequence, all travel times will increase if $X < C$. This can easily be understood, because the objective is to reduce high noise levels. Therefore flows on these links must be reduced. In the chosen user optimization this can only be realized by increasing travel time on these links. As a consequence, alternative routes that originally were longer become attractive. This is shown in Figure 1a for the Bureau of Public Roads (BPR) function *(7)*. Figure 1b shows how the resulting increase in travel time would be realized in practice: it is easier to increase the free-flow travel time than to reduce the link capacity. The possibilities for these practical realizations have been investigated in a follow-up study *(8)*.

The reason for the conversion presented above is that an extra constraint like $f_a > X_a$, for all a, might make a feasible solution impossible. Furthermore, equilibrium according to Wardrop's first principle might become impossible as well.

The maximum flow of each link is called the environmental capacity (EC). These environmental capacities have a minimum value of 245 vehicles/hr because the current legal standards only cover roads with a minimum flow of 2,450 vehicles per day.

It should be noted that a real noise optimum will not be obtained. The result is one of a set of feasible solutions. In the results section, an analysis will be presented for a moderately large Dutch town in 1995, for which year a population of 85,000 inhabitants is projected. The network contains 264 nodes—among them 57 centroids—and 766 links.

THE ASSIGNMENT MODEL

Description

Although it is not impossible for the environmental capacity to be exceeded, this should not occur. Traffic on oversaturated links should be redistributed over the network. It is important, therefore, to choose a good link travel-time function. Both Davidson's hyperbolic function *(7, 9)* and the BPR polynomial have proved to be good delay functions. The Davidson function was expected to result in a more pronounced redistribution because of the asymptote at capacity.

BPR:

$$t = t_0 \cdot [1 + 0.15 \cdot (f/C)^4] \tag{5}$$

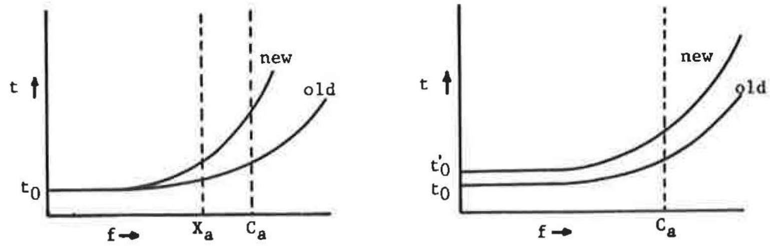
Davidson:

$$t = t_0 \cdot \left[\frac{1 - 0.6\,(f/C)}{1 - (f/C)}\right] \quad (f < C) \tag{6}$$

For computational reasons the hyperbolic function is extended with a linear part for saturation degrees of 0.99 and over.

To test this assumption, the assignment was performed with both functions.

The Dutch legal standards offer two calculation methods *(10, 11)*. One method is very exact and detailed, which makes it unsuitable for the calculation of noise levels on such a large



a) Reduction of the capacity b) Increase of the free-flow travel time

FIGURE 1 Alternatives to increase link travel time.

scale as is intended here. Therefore the other method was used, from which the environmental capacity can be derived as follows:

$$X = \frac{d}{p_1 \cdot 10^{y(1)} + p_m \cdot 10^{y(m)} + p_z \cdot 10^{y(z)}} \cdot 10^{L_{max}/10} \quad (7)$$

where

$y(1)$ = $5.12 + 0.021 * v - \log v$,
$y(m)$ = $6.84 + 0.009 * v - \log v$,
$y(z)$ = $7.62 + 0.003 * v - \log v$,
p_1 = percentage of automobiles,
p_m = percentage of medium-heavy traffic,
p_z = percentage of heavy traffic,
v = speed (km/hr),
d = facade distance (m), and
L_{max} = noise standard [dB(A)].

Input

The network was divided into different link types, each with its specific traffic composition, speed, and theoretical capacity. For roads within the built-up area p_1 ranges from 0.94 to 1.00, p_m ranges from 0 to 0.004, and p_z from 0 to 0.02. Only the facade distance may differ for each separate link.

However, in a network description, a road consists of two directed links. Therefore, a final point to be dealt with was the fact that assignments are performed for each directed link separately, whereas the noise level on a road is dependent on the flow on both links together. In the model a 50-50 division of the total flow on a two-way road is assumed, corresponding to a maximum flow per link of half of the environmental capacity. This is the most unfavorable and therefore the safest assumption; a full utilization of the road capacity will seldom occur under these conditions.

Sensitivity Analysis

To determine the trade-offs between the variables in the model, a simple sensitivity analysis of the noise-level calculation was carried out. The results are as follows:

1. A 1-dB(A) elevation of the noise standard corresponds to a 26 percent increase in the environmental capacity; every 3-dB(A) elevation results in a doubling of *EC*.

2. The influence of heavy traffic on the noise level—and thus on the environmental capacity—is considerable, especially in built-up areas, as can be seen from Table 1.

3. The direct influence of speed on environmental capacity turned out to be very small in built-up areas. A 35-km/hr speed results in X = 304 vehicles/hr and a 55-km/hr speed results in X = 288 vehicle/hr. The environmental capacity reaches a maximum at ±45 km/hr.

TABLE 1 EXAMPLE OF INFLUENCE OF HEAVY TRAFFIC ON NOISE LEVEL

p_1	p_m	p_z	X	f_1	f_m	f_z
0.94	0.04	0.02	308	290	12	6
1	0	0	778	778	0	0

NOTE: d = 20 m; L_{max} = 60 dB(A); V = 45 km/hr; X = environmental capacity (vehicles/hr); $f_1 = p_1 \cdot X$ (vehicles/hr); $f_m = p_m \cdot X$; $f_z = p_z \cdot X$.

4. Environmental capacity is inversely proportional to the facade distance, which is responsible for the lower environmental capacity of most streets in a built-up area as opposed to their theoretical traffic capacity.

RESULTS

Criteria

First the following four alternatives were calculated and compared:

1. An assignment model with Davidson's travel-time function and extended with noise standards,
2. An assignment model with the BPR travel-time function and extended with noise standards,
3. An assignment with Davidson's function without additional constraints, and
4. An assignment with the BPR function without additional constraints.

Comparisons were made by observing the differences between Alternatives 1 and 2 and 3 and 4. These differences happened to be very small, so it was decided to perform the rest of the assignments with only the BPR polynomial. The expected advantages of the hyperbolic function did not show up and a disadvantage of this function is that the travel-time values became very large and hard to handle when full capacity is approached.

Alternatives 2 and 4 have been compared on the basis of the following five criteria:

1. The number of links in each noise bracket i (i = 1, . . . , 5). For noise levels beyond the noise standard of 60 dB(A), noise brackets of 3 dB(A) have been defined, because this bracket size corresponds to a doubling of the traffic flow.
2. A noise index value INi for each bracket. By adding the lengths of all road sections within one bracket, weighted noise index values were obtained.
3. A total noise index value $INTOT$ for the whole network. For each bracket the noise index value INi is multiplied by an annoyance factor c_i. The products, added over all brackets, give the $INTOT$ value. The annoyance factors were derived by Wardrop (*1*). The noise standard L_{max} = 60 dB(A) corresponds to a factor equal to 1; an excess of x dB(A) results in an annoyance factor $c_i = \exp(0.1143x)$ (Table 2).

TABLE 2 ANNOYANCE FACTORS BY NOISE LEVEL

Noise Level No.	Range [dB(A)]	Avg. Exceeding	Annoyance Factor c_i
1	60–63	1.5	1.19
2	63–66	4.5	1.68
3	66–69	7.5	2.36
4	69–72	10.5	3.32
5	>72	13.5[a]	4.68

[a]Estimated.

4. The total travel performance in vehicle kilometers.
5. The saturation degree. To get an impression of the eventual oversaturation throughout the network, the average saturation degree for the busiest directions of all roads together and the quietest directions of all roads together are determined. Alternative 2 will always show larger values than Alternative 4 because most saturation degrees depend on the environmental capacity (which usually is smaller than the theoretical capacity).

Analysis

At first the results were rather poor and disappointing. The number of road sections where the noise standard was exceeded had increased (rather than decreased) by 30 percent and the total travel performance increased by 64 to 75 percent. A closer observation of the plots, however, showed several locations where the input specifications required modification. One such location was a highway north of the town with an important traffic function. A low environmental capacity for such a road is not realistic. In these cases it is better not to impose any restrictions on the flow and to install effective noise-reducing facilities if necessary.

Furthermore, the network structure was improved.. As a consequence the number of links (including dummy links connecting centroids to the network) increased to 859. The results of the model at this stage are shown in Table 3. Redistribution of the traffic (in order to reduce the noise levels) now resulted in a 21 percent increase in travel performance versus a 6 percent improvement in the total index value $INTOT$.

TABLE 3 COMPARISON OF RESULTS

Criterion	BPR Function: With Extra Constraint	BPR Function: Without Extra Constraint
No. of road sections		
$60 < L \leq 63$ (i = 1)	55	24
$63 < L \leq 66$ (i = 2)	24	30
$66 < L \leq 69$ (i = 3)	13	28
$69 < L \leq 72$ (i = 4)	0	3
$L > 72$ (i = 5)	0	0
Total	92	85
Noise index value (m)		
$IN1 = \sum_{a \varepsilon i} 1 * 1{,}000$	15 400	7230
$IN2 = \sum_{a \varepsilon i} 1 * 1{,}000$	7 570	8790
$IN3 = \sum_{a \varepsilon i} 1 * 1{,}000$	4 310	7650
$IN4 = \sum_{a \varepsilon i} 1 * 1{,}000$	0	690
$IN5 = \sum_{a \varepsilon i} 1 * 1{,}000$	0	0
Total noise index value (m), $INTOT = \sum_i c_i * INi$	41 140	43 628
Travel performance (vehicle-km)	108 717	89 750
Average f/C (%)		
Quiet	35.4	15.7
Busy	44.8	20.3

It is obvious that noise levels higher than 66 dB(A) are stongely reduced by incorporating the noise standard. Moreover, more than half of the noise levels in the 60- to 63-dB(A) noise bracket are less than 61 dB(A). The fact that the total number of noise levels exceeded has increased follows from the equilibrium principle: alternative routes are used and travel distances increase.

Figure 2 shows these phenomena quite clearly. It shows the total length of the road sections where a certain noise level is exceeded as a function of this noise level.

The findings corroborate the earlier hypothesis that traffic flows on noise-sensitive roads are indeed reduced and flows on undersaturated roads are increased. The flow reductions, however, are not always sufficient to guarantee a noise level of 60 dB(A) or less in the new situation.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the comparison of the alternatives, the following conclusions were reached:

1. Mechanical application of the model may lead to wrong and unfavorable results. In particular, roads or road sections that should serve or maintain an important traffic function must be selected beforehand. Such roads have to be treated as described in the previous section for the highway north of the town.
2. The results and improvements that can be obtained are dependent on the size and structure of the network. When few

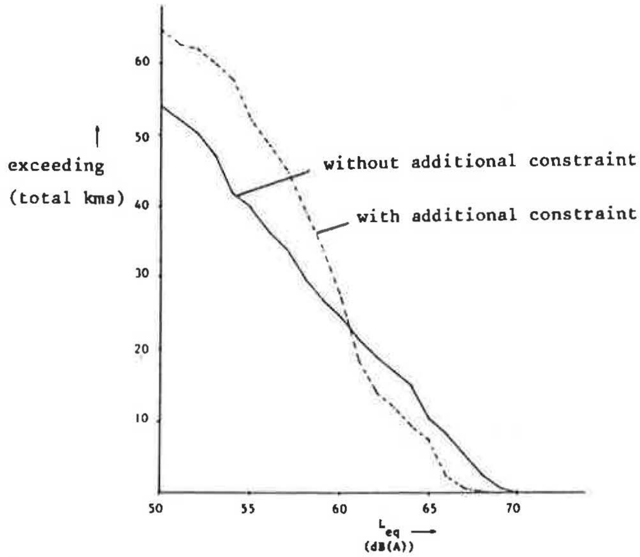


FIGURE 2 Total length of road sections where noise level is exceeded as a function of that noise level.

alterative routes are available, the possible improvements will be moderate, but when many surrounding roads are taken into account, redistribution of traffic is possible but will result in a strong increase in the total travel performance.

3. One should be aware that the final result is not an optimum, but only one of a series of possible solutions that meet the given constraints as closely as possible.

4. It is always dangerous to weight the results because it may resemble manipulation. However, in this case a mere unweighted comparison of the results could have resulted in a serious misinterpretation. Of the different ways to weight, the simplest and most transparent one was chosen.

The redistribution of traffic in this test case led to obvious improvements for the inhabitants of the city. Instances of exceeding the noise standard by 6 dB(A) or more decreased by 58 percent, whereas 28 of the 55 instances in the 60- to 63-dB(A) noise bracket are less than 61 dB(A), an amount that cannot even be perceived by the human ear.

However, it is questionable whether similar improvements can be expected in every arbitrary network. Furthermore, the differences between actual travel time and desirable travel time need to be moderate to make practical realization possible.

The results, however, can be further improved by perfecting some aspects of the model. The following recommendations are made:

- Introduction of a separate O-D table for heavy traffic, because of the considerable influence of this category.
- Introduction of the number of houses or the number of inhabitants per link in order to get a more exact weighting of the results.
- Performance of a true minimization of the noise annoyance to get an impression of the maximum improvement that can be obtained.

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