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Comparison of a Gaussian diffusion model with guidelines for calculating the separation distance between livestock farming and residential areas to avoid odour annoyance

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Abstract

Complaints by the neighbourhood due to odour pollution from livestock farming are increasing. Therefore, some countries have already developed guidelines to address odour from livestock. These guidelines are in use to assess the necessary separation distance between livestock buildings and residential areas such that odour is not felt as an annoyance. In all these guidelines, the separation distance is calculated as a function of the rate of pollution. These are mainly power functions with an exponent between 0.3 and 0.5. The Austrian regulatory dispersion model, a Gauss model, is used to calculate the frequency distribution of the dilution factor for 12 classes of distances between 50 and 500 m downwind from the source. These data were fitted to an extended Weibull distribution of the dilution factor to determine the exponent of the power function describing the separation distance as a function of the emission. The exponent has a value of about 0.72. This result, achieved with a wind and stability statistics representative for the Austrian flatlands north of the Alps, indicates a stronger dependance of the separation distance from the odour emission than suggested by the guidelines. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Odour; Guidelines; Animal; Regulatory model; Gauss model; Separation distance

1. Introduction

Livestock farming is increasingly confronted with questions of environmental protection because of different kinds of pollutants brought into the atmosphere. One of them is odour which is a very important component because the acceptance of livestock farming in the vicinity can decrease due to an increase in odour sensation.

The concentration of odoriphores can be handled like other volatile pollutants. The dispersion of such substances can be described by well-known dispersion models, like a Gaussian one (e.g. Kolb, 1981; ÖNorm M 9440, 1992/96). Then the concentration at a receptor point is calculated as a mean value of the concentration of odoriphores for a defined period (e.g. half-hour, 3 h mean value). The calculation of the odorant concentration itself is not meaningful if odour has to be evaluated. This is due to the fact that odour is not an attribute of an odoriphor, but a reaction of humans (Summer, 1970).

The odour sensation is triggered by the odour stimulus and characterised by intensity and frequency. To predict these parameters it is necessary to consider short-term fluctuations of odourant concentrations at the receptor point. Odour sensation can only be observed

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if the odourant concentration is higher than the odour threshold of the substances. Due to fluctuations an odour sensation can take place even if the mean odourant concentration is lower than the odour threshold.

Odour sensation might cause annoyance depending on the individual and sociological situation of a person. Local authorities especially seek procedures to cope with increasing complaints by neighbours. Therefore, some countries have already developed guidelines to address odour from livestock. These guidelines are in use to assess the necessary separation distance between livestock buildings as the source of odour and residential areas such that odour is not felt as an annoyance. They are mainly based on a simple parameterisation of the odour source, the dilution of the emission and the assessment of the protection level depending on the land use category. The application results in calculating a separation distance to the neighbourhood which guarantees a far-reaching protection against odour annoyance.

In all these guidelines, the separation distance is calculated as a function of the rate of pollution. These are mainly power functions with an exponent between 0.3 and 0.5. The exponent and therefore the shape of the curve used describes the sensitivity of the separation distance to the odour pollution. There is, however, no profound reason for using just this range of exponents except the fact that the resulting separation distances are of the correct order of magnitude, i.e. up to several hundreds of meters. There is also no systematic verification of separation distances by olfactometric measurements comprising a lot of livestock farms, topographical and meteorological conditions. The procedure to determine the shape of the curve and thereby also the exponent of the function applied in the German guidelines is discussed by Schirz (1989, 1997). The function was calculated by using the threshold distance of odour recognition of a panel of just 3 or 4 persons. The statistics of wind and of stability of the atmosphere was not taken into account. The conclusion from single experiments to a separation distance valid over the whole year seems therefore to be weak.

The motivation of the study presented here is to investigate if, by using an independant method, the sensitivity of the separation distance to the odour pollution is correctly described by the various guidelines. This will be accomplished by using a Gauss model to derive the frequency distribution of the dilution factor during daytime for distances between 50 and 500 m downwind from the source and fitting these data to an extended Weibull distribution of the dilution factor to determine the exponent of the power function describing the separation distance as a function of the emission. The exponent calculated will be compared to the exponents of the guidelines. Since the frequency distributions will be calculated with the aid of wind and stability statistics representative for the Austrian flatlands north of the Alps, the results can be taken as a first step encouraging future investigations.

In the next section, the calculation of separation distances by various national guidelines is outlined. The method to calculate the exponent by the Gauss model is presented in Section 3. The results and a discussion follow in Sections 4 and 5.

2. Separation distance calculated by various national guidelines

The calculation of a separation distance between residential houses and livestock buildings is a common objective of various guidelines of the European countries. The structure of the guidelines is very similar in most cases. First of all the odour source is assessed by the number of animals and additionally by some parameters which influence the odour pollution. On the basis of the odour source, the separation distance is calculated by using an empirical function, generally for the land use category of pure residential areas. In the last step this separation distance is modified by a reduction factor to adapt the separation distance to the level of various claims of odour-free environments depending on the land use category.

2.1. Austria

The Austrian guideline (Schauberger et al., 1997; Schauberger and Piringer, 1997a, b) is based on a rough estimate of the source by the following parameters: number of farm animals, their use and the way they are kept, the geometry of the outlet air, the vertical velocity of the outlet air, the manipulation of manure inside the livestock building, the kind of manure storage and the way of feeding. As a result, the so-called odour number is calculated. Thereafter, the separation distance is estimated by a power function using an exponent of 0.5. Next, the dispersion of odour is assessed by modifying the separation distance. In the Austrian guideline, due to the mostly complex topography, this step is treated more substantially than elsewhere. The separation distance is first modified by using the mean distribution of the wind direction at the site characterizing the climatological situation and second by estimating the predominant local winds and stability (e.g. valley wind circulation) considering the local topography. At the end the legal claim of protection by the surrounding residential areas is additionally taken into account. The treatment of dispersion and legal claim of protection results in a final separation distance depending on the direction to the neighbours.

2.2. Germany

In Germany separate guidelines for pigs (VDI 3471, 1986), cattle (VDI 3473, 1994) and poultry (VDI 3472, 1986) are used. These three guidelines are well documented and described (Paduch, 1988).

In a first step, the odour source of a livestock farm is assessed by the number of livestock units (live mass of animals normalised by 500 kg). In a second step, the manure handling, the ventilation system, the type of feed and the topography of the site are evaluated by assigning scores to each category. The scores SC are summed up. For four different classes of total scores (a value of 100 for an excellent situation with low odour emission down to a value of 25 for high odour emission in steps of 25), the separation distances are fixed by graphs.

For pigs, the separation distance S (m) can be calculated by a power law as a function of the emission E (livestock unit LU, LU = body mass of the animals normalised by 500 kg) (CIGR, 1994):

$$\text{for a score of 100: } S = 50.2E^{0.32} \quad (1a)$$

$$\text{for a score of 25: } S = 86.3E^{0.32}. \quad (1b)$$

Krause (1992) calculates the factor and the exponent by a polynom of second order as

$$S = a(\mathrm{SC})E^{b(\mathrm{SC})} \quad (2)$$

$$\text{with } a(\mathrm{SC}) = a_0 + a_1\,\mathrm{SC} + a_2\,\mathrm{SC}^2 \quad (3a)$$

$$\text{and } b(\mathrm{SC}) = b_0 + b_1\,\mathrm{SC} + b_2\,\mathrm{SC}^2. \quad (3b)$$

The polynomial coefficients are summarized for pigs (VDI 4371, 1986) and for poultry (VDI 4372, 1986) in Table 1.

2.3. Switzerland

In the Swiss guideline (Richner and Schmidlin, 1995), the pollution is assessed by the number of animals and a weighting factor which depends on the annoying potential of the kind of animals which are kept. The product of these two factors gives the odour load. The standard separation distance is calculated by a logarithmic function. It is modified by nine factors covering the shape of the site, the sea level, the manure handling system, the kind of manure which is produced, the cleanliness of the farm, nutrition, ventilation system and measures to abate odour release due to the ventilation system or the storage of manure.

In the Swiss guideline, the separation distance is calculated by a logarithmic function. This function, in its range of validity, can be fit to a power law whose exponent would be 0.33.

Table 1
Polynomial coefficients of the factors a(SC) (Eq. (3a)) and the exponent b (SC) of the power function (Eq. (3b)) for score SC between 25 and 100 (Krause, 1992)

Polynomial coefficients	Pigs VDI 4371, 1986	Poultry VDI 4372, 1986
a_0	103.027	134.3505
a_1	− 0.6963	− 1.3979
a_2	0.00153	0.006847
b_0	0.307	0.26353
b_1	0.0051	0.001821
b_2	− 0.000002	− 0.000013

2.4. The Netherlands

The separation distance is calculated as a function of pig fattening places (number of pigs the animal house is built for; Ministrie van Landbouw, 1991). For other species a conversion factor is defined in relation to a fattening pig. Additional parameters known from other guidelines already discussed are neglected. The graph of this guideline is fitted to a power function with an exponent of 0.50.

A reduction factor is applied to all these national guidelines to fit the calculated separation distance to land use categories (Schauberger and Piringer, 1997a, b). The shape of the functions used to calculate the separation distance is investigated by using only the values for pure residential areas. In Fig. 1 the separation distances for fattening pigs are compared for two different cases: $E+/D-$, combining a high level of odour ($E+$) and an unfavourable situation for dilution ($D-$) and $E-/D+$, combining a low odour level ($E-$) and favourable dilution ($D+$).

The separation distances, determined by the various guidelines taking the same odour source scenario into account, differ a lot. As apparent from the discussion of the exponents above, the increase in separation distance with the number of animals is more rapid for the Austrian and the Dutch compared to the German and the Swiss guidelines. The Swiss guideline shows the largest, the German guideline the smallest variation of separation distances between the most favourable and the most unfavourable situations. The Austrian guideline has a tendency to estimate lower separation distances than the other guidelines. Fig. 1 clearly shows the need for investigating the dependance of the separation distance from the odour emission by a model independent of the guidelines. The method is explained in the next section.

3. Model calculations and statistics

The cumulative frequency distribution of the dilution factor D is calculated by the Austrian regulatory dispersion model (ÖNorm M 9440, 1992/96; Kolb, 1981) by

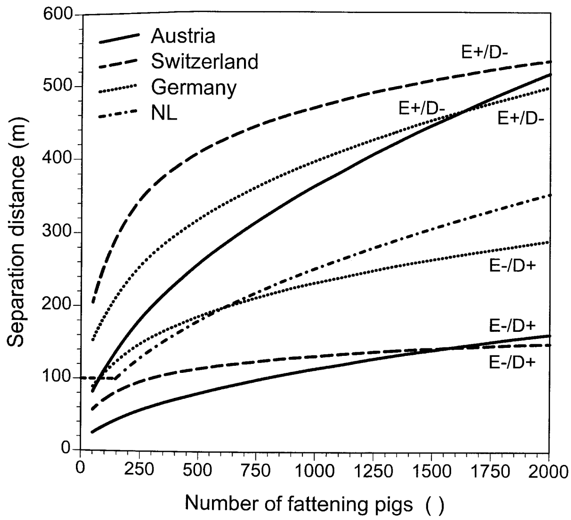

Fig. 1. Separation distance S calculated by the Austrian, German, Swiss and Dutch (NL) guidelines for fattening pigs. Two cases: $E+/D-$, combining a high level of odour ($E+$) and an unfavourable situation for dilution ($D-$); $E-/D+$, combining a low odour level ($E-$) and favourable dilution ($D+$). The graph of the Dutch guideline is the minimum separation distance without any variability depending on the emission or the dilution. For all guidelines, the separation distance is calculated for an area which is intended for recreation purpose and pure residential use.

making use of a statistics of stability classes representative for the Austrian flatlands north of the Alps.

The regulatory model is a Gaussian plume model applied for single stack emissions and distances up to 15 km. Plume rise formulae used in the model are a combination of formulae suggested by Carson and Moses (1969) and Briggs (1975). The model uses a traditional discrete stability classification scheme with dispersion parameters developed by Reuter (1970). Stability classes are determined as a function of half-hourly mean wind speed and a combination of sun elevation angle and cloud cover. Within this scheme, classes 2–7 can occur in Austria. Stability classes 2 and 3 occur during daytime in a well-mixed boundary layer, class 3 allowing also for cases of high wind velocity and moderate cloud cover. Class 4 is representative for cloudy and/or windy conditions including precipitation or fog and can occur day and night. In the flatlands, it is by far the most common dispersion category. Classes 5–7 occur at night, static stability increasing with class number.

In the following, the daytime situation during summer will be investigated. The statistics of dispersion conditions, i.e. the probabilities of the combinations of stability classes and wind velocities used, is given in Table 2. The sum of probabilities amounts to 1000‰ (all cases). The probabilities generally decrease with increasing wind speed; however for stability class 4, wind velocities of 2 and 3 m s^{-1} are more common than weak winds of 1 m s^{-1}.

Table 2
Probabilities (‰) of the combinations of atmospheric stability classes (Reuter, 1970) and wind velocities during daytime representative for the Austrian flatlands north of the Alps

Class of stability	Wind velocity (m s^{-1})	Probability (%)
2	1	130
2	2	77
2	3	37
2	4	21
3	1	180
3	2	88
3	3	42
3	4	25
3	5	11
3	6	1
4	1	56
4	2	115
4	3	119
4	4	60
4	5	20
4	6	14
4	7	3
4	8	1

The regulatory model calculates half hour mean concentrations. The sensation of odour, however, depends on the momentary odour concentration and not on a mean value over a long time of integration. Smith (1973) gives the following relationship:

$$\frac{C_p}{C_m} = \left(\frac{t_m}{t_p}\right)^u \tag{4}$$

with the mean concentration C_m calculated for an integration time of t_m and the peak concentration C_p for an integration time of t_p. The exponent u depends on the stability of the atmosphere and assumes values of 0.35 (class 4), 0.52 (class 3) and 0.65 (class 2). From wind spectrum analysis (Courtney et al., 1990), short-term concentration fluctuations peak at about 100 s. Using $t_m = 1800$ s and $t_p = 100$ s, the following peak to mean factors, depending on atmospheric stability, are derived: 6.5 for diffusion category 2, 4.5 for diffusion category 3 and 2.8 for diffusion category 4.

The model calculations were done for nine scenarios with the relative emission varying between 0.04 and 4. The odour concentration of this volume flow was assumed to be constant with 500 OU m^{-3} (Oldenburg, 1989; Krause, 1992). The result of the model calculation is the cumulative frequency distribution of the peak (maximum) concentrations derived for all combinations of stability class and wind velocity (Table 2). This calculation is done for 10 distances from the pollutant source starting with 50 m up to 500 m in increments of 50 m. These data were fitted to an extended Weibull distribution WBD of the dilution factor D, defined as the ratio of the constant odour concentration of the volume flow to the peak concentration at a distance x_i:

$$\mathrm{WBD}(x_i) = 1 - \exp\left[-\left(\frac{D - D_0}{c} \right)^d \right] \tag{5}$$

with the three parameters D_0, c and d. The advantage of the extended Weibull distribution compared to the normal one is the parameter D_0 used as an off-set of the distribution, so that the probability is zero for a dilution factor smaller than D_0 (Fig. 2). Measurements by Jones (1979) demonstrate the suitability of this distribution to fit the calculated dilution factors.

The parameters were fitted by an iterative method on the basis of minimizing the square residuals. Three statistical parameters were used to evaluate the goodness of the fit: (1) the coefficient of determination r^2, adjusted to the degree of freedom (Eq. (6)), (2) the root mean square error of the fitted function RMSE (Eq. (7)) and (3) the F value used to describe the suitability of the selected distribution (Eq. (8)).

The coefficient of determination r^2, adjusted to the degree of freedom is given by:

$$r^2 = 1 - \frac{\sum_j^n (P_j - P_j^m)^2 \, n - 1}{\sum_j^n (P_j - \bar{P})^2 \, n - m - 1} \tag{6}$$

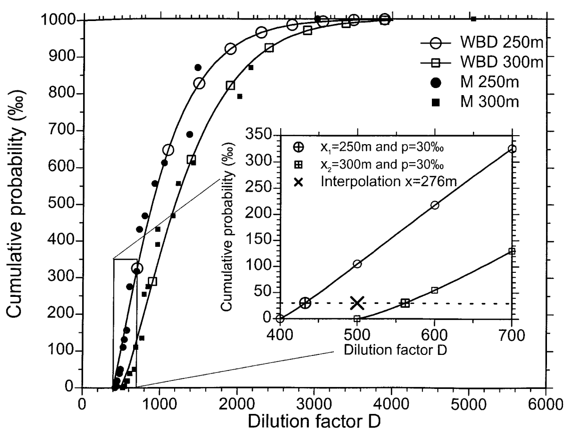

Fig. 2. Example of the linear interpolation of the separation distance for an exceeding probability of 30‰ (dotted line in the enlarged part) and a dilution factor of 500 which gives an odour concentration of 1 OU m^{-3} . The two Weibull distribution functions WBD for a distance $x_0 = 250$ m and $x_1 = 300$ m (empty symbols) are calculated for a relative emission of 1.00 (bold line in Table 3). Besides the two fitted WBD, the corresponding values of the Gaussian model calculation are shown, too (model calculation M; filled symbols).

with the cumulated probability of the model calculation P_j, the fitted distribution model P_j^m and the mean value $\bar{P}$, the number of data points n, the number of coefficients m (for the extended WBD $m = 3$, for the power function $m = 2$).

The RMSE is calculated by

$$\mathrm{RMSE} = \frac{\sum_j^n (P_j - P_j^m)^2}{n - m} \tag{7}$$

with the same units as the P_j and P_j^m.

The F value is given by

$$F = \frac{\dfrac{\sum_j^n (P_j - \bar{P})^2 - \sum_j^n (P_j - P_j^m)^2}{m - 1}}{\dfrac{\sum_j^n (P_j - p_j^m)^2}{(n - m)}}. \tag{8}$$

The F value can be interpreted as the quotient between the variance about the mean and the variance caused by the model. The value can be used to describe how accurately a given model can describe the data. For larger values of F, the variance of the fitted data is reduced due to good selection of the function and its parameters.

The fitted distribution functions were used to calculate the appropriate distance where the requirements are fulfilled that for an exceeding probability $p = 30‰$ over the summer half-year (April–September) the limiting dilution factor D_L is equal to 500, resulting in an odour concentration at the receptor point of 1 OU m^{-3} for this period. This concentration is equivalent to the threshold value of odour sensation. The exceeding probability selected is based on the threshold values which are used in some European countries (Kypke, 1994; Hobson, 1997). The combination $p = 30‰$ and $D_L = 500$ is mainly used for pure residential areas in Germany.

In Fig. 2, the linear interpolation is demonstrated for an example of a relative emission of 1.00. The distance for a given dilution factor and exceeding probability (in this case $D_L = 500$; $p = 30‰$) is calculated by linear interpolation (see also enlarged part of Fig. 2):

$$x = x_0 + \frac{x_1 - x_0}{D_{1,p} - D_{0,p}} (D_{0,p} - D_L) \tag{9}$$

with the distances x_0 and x_1 for which the distribution function was fitted, the dilution factors $D_{0,p}$ and $D_{1,p}$ calculated for a certain exceeding probability (here 30‰) by the inverse Weibull distribution WBD^{-1} and the lower limit of the dilution factor D_L (here 500). The inverse Weibull distribution WBD^{-1} is given by

$$\mathrm{WBD}^{-1}(p) = D_0 + c[-\ln(1 - p)]^{1/d} \tag{10}$$

with the three function parameters D_0, c and d of Eq. (5). The distance x can be interpreted as a separation distance S, valid for a certain exceeding probability (here $p = 30‰$) and a dilution factor (here $D_L = 500$). By linear interpolation between the extended Weibull distributions for a distance of $x_0 = 250$ m and $x_1 = 300$ m, a separation distance x of 276 m is calculated (Fig. 2).

The separation distances x were calculated for all nine emission cases. For the first case (relative emission 0.04) the separation distance was smaller than 50 m so that this case was not used for further calculations. A power function was fitted to these eight distances x.

$$S(p, D) = aE^{b} \qquad (11)$$

with the relative separation distance $S(p, D)$ depending on the emission E and the two function parameters a and b.

4. Results

The dependance of the separation distance on the emission among the different guidelines was the primary interest of this investigation. Instead of an absolute comparison of separation distances, a comparison of the exponent b of the power function and therefore the shape of the curves was intended.

The result of the fitted WBD (Eq. (5)), which is used for the interpolation, is summarized in Table 3. Besides these parameters, also the statistical parameters to evaluate the fit parameters r (Eq. (6)), RMSE (Eq. (7)) and F (Eq. (8)) and the distance x calculated by linear interpolation (Eq. (9)) for an exceeding probability of $p = 30‰$ are shown. The parameters are calculated for eight emission scenarios from a relative emission of 0.10 up to 4.0. For each case the upper (x_0) and lower (x_1) fit of the extended Weibull distribution is used to calculate the threshold distance x for a certain exceeding probability $p = 30‰$ and dilution limit $D_L = 500$ by linear interpolation. For the lower WBD (closer to the odour source) the dilution factor is lower than the selected limit of $D_L = 500$ (crossed circle in the zoomed part of Fig. 2), for the upper WBD (more distant from the source) the dilution factor is larger than the selected limit of $D_L = 500$ (crossed square in the zoomed part of Fig. 2). Besides the selected exceeding probability of 30‰, these calculations are also done for exceeding probabilities of 10‰, 50‰, and 80‰, respectively. By changing the exceeding probability, the influence of the selected values on the exponent of the power function is investigated. The result is shown in Table 4, where the exponent of the power law (Eq. (11)) and the statistical parameters r^2 (Eq. (6)), F (Eq. (7)) and RMSE (Eq. (8)) of the data fit are given.

The exponent b of the power function increases slightly with the exceeding probability and assumes a value of about 0.72 in the mean. The quality of the fit also increases with increasing exceeding probability because the uncertainty of the fit increases towards the tails of the fitted function (Fig. 2).

Table 3
Parameters of the extended Weibull distribution WBD (Eq. (5)) for the model calculation and statistical parameters of the fit. For each case of relative emission rate, the upper and lower WBD was selected, for which the separation distance was calculated by linear interpolation for a dilution factor of $D_L = 500$ and the exceeding probability $p = 30‰$. The bold line indicates the values used for Fig. 2. (The values of the fit and the linear interpolation of exceeding probabilities of 10, 50, and 80‰, respectively are not presented in this table)

Relative emission	Lower WBD x_0	D_0	c	d	r	F	RMSE	Upper WBD x_1	D_0	c	d	r	F	RMSE	Linear interpolation x
0.10	50	258.2	759.5	3.0979	0.9732	332.14	53.25	100	1100.0	1191.3	1.4633	0.9269	117.03	79.84	50
0.20	50	182.3	323.9	2.6993	0.9741	344.15	52.34	100	547.6	591.6	1.4156	0.9295	121.65	78.40	85
0.30	100	366.3	421.1	1.4022	0.9204	106.88	82.98	150	599.9	812.3	1.6396	0.9800	448.53	41.96	117
0.40	100	263.7	314.8	1.3250	0.9251	114.06	80.66	150	499.3	576.2	1.2743	0.9625	235.46	57.53	143
1.00	**250**	**399.8**	**673.9**	**1.1551**	**0.9632**	**239.69**	**59.16**	**300**	**499.6**	**919.6**	**1.2959**	**0.9767**	**384.14**	**47.75**	**276**
2.00	400	398.8	816.5	1.0519	0.9860	643.81	36.54	450	500.0	991.3	1.0538	0.9877	735.67	34.21	433
3.00	650	262.2	1571.1	1.8010	0.9639	244.71	56.82	700	465.7	1326.0	1.6026	0.9468	163.69	68.58	655
4.00	700	400.0	1139.8	1.0730	0.9664	235.36	45.50	750	472.8	1442.9	1.2373	0.9749	316.69	38.46	724

Table 4
Exponent b of the power function (fitted values ± standard deviation) describing the separation distance S as a function of the emission E for four different exceeding probabilities. The dilution factor was fixed to 500 so that the odour concentration is 1 OU m for the calculated separation distance

Exceeding probability p	10‰	30‰	50‰	80‰
Exponent b	0.714 ± 0.043	0.719 ± 0.036	0.722 ± 0.026	0.726 ± 0.009
r^2	0.987	0.991	0.996	0.999
F	651.90	923.79	1868.81	15763.74
RMSE	28.25	22.97	15.68	5.14

5. Discussion

The primary interest of all the guidelines discussed is not the perception of odour but to avoid odour annoyance. The objective of the Austrian guideline (Schauberger et al., 1997) is to determine "*a separation distance to the neighbourhood which guarantees a far-reaching protection against odour annoyance*". The German guidelines "*try to avoid considerable annoyance by odour*" (VDI 3471, 1986; VDI 3472, 1986; VDI 3473, 1994). The Swiss guideline was conceived as recommendation of minimum separation distances (Richner and Schmidlin, 1995) to fulfil the requests of the environmental protection act.

These guidelines calculate a separation distance as a function of the odour source. Although the separation distances of all the guidelines discussed can be fitted to a power law, a wide variety of the exponent ($0.32 \leqslant b \leqslant 0.50$) can be observed which influences the shape of the curves to quite an extent (Fig. 1).

The Austrian (A) and Dutch (NL) guidelines use an exponent of 0.50. For the Austrian guideline the exponent was deduced from the decrease of ground centerline concentrations with distance from the source for distances larger than the maximum concentration (Kolb, 1981). For the German guidelines Schirz (1989) gives an overview how the shape of the function to calculate the separation distance was determined. About 600 livestock farms were investigated by a panel of three to four persons. On the basis of these data the calculated separation distance was enlarged by about 100% to support the expectation that this separation distance is a protection against odour annoyance.

To compare the shape of the different power functions which are used to calculate the separation distance, both variables (source strength and separation distance) were normalised to unity ($a = 1$). In Fig. 3, three different values of the exponent of the power function are compared. An exponent $b = 0.32$ is used by the German and the Swiss guidelines. The exponent of the Austrian and Dutch guidelines is $b = 0.50$, and the result of the model calculations is $b = 0.72$.

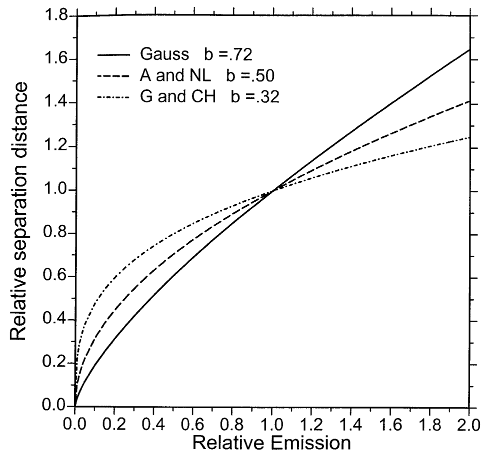

Fig. 3. Relative separation distance (normalised by a factor $a = 1$; Eq. (11)) as a function of the relative source strength calculated by the Austrian (A) and Dutch (NL) guidelines with an exponent $b = 0.50$, the German (G) and the Swiss (CH) guidelines with an exponent $b = 0.32$, and the result of the model calculation using the Gaussian diffusion model (Gauss) with an exponent $b = 0.72$.

All guidelines show a flatter shape of the curve compared to the Gaussian diffusion model. The biggest deviation is caused by the German and Swiss functions, followed by the Austrian and Dutch ones. This result, achieved with a wind and stability statistics representative for the Austrian flatlands north of the Alps, indicates a stronger dependence of the separation distance from the odour emission than suggested by the guidelines.

The use of the Gaussian regulatory model ÖNorm M9440 (1992/96) to calculate dilution factors imposes some restrictions to the generalization of the results achieved. The model is applicable only in flat terrain. Building influence on the dispersion as well as the influence of low-level capping inversions on the concentrations are not considered. The model is reliable only for wind velocity equal to or above 1 m s^{-1} and is advised to be applied for distances equal to or larger than 100 m. Treating more complex meteorological or topographic conditions, more elaborate dispersion models have to be used. The restrictions are, however, not very severe because a lot of large livestock farms in Austria are situated in rather flat terrain. Concentrations during calm wind conditions could be considered in a first step according to ÖNorm M9440 (1992/96) by multiplying by 1.5 the concentration for 1 m s^{-1} and the appropriate stability class.

The statistics of stability classes used for the calculation of the frequencies of the dilution factors is representative for the Austrian flatlands north of the Alps. These areas are characterized by good ventilation throughout the year, so complex flow structures like periodically changing wind regimes or frequent stagnant wind situations, when the regulatory model cannot be applied, do not occur.

The selected odour concentration of the source is equal to a rough estimate for a pig fattening unit based on measurements of Oldenburg (1989). The agricultural structure of the investigated livestock farms is very similar to the Austrian ones. The dilution factors are calculated for summertime conditions. During summer, the odour annoyance is far more pronounced than in winter because people intend to stay out more frequently or keep windows open. Moreover, the odour concentration of the outlet air of livestock buildings increase with temperature (Oldenburg, 1989). The calculations were done for daytime conditions. They are more easily assessed because dilution is a function of distance during daytime. Vertical mixing decreases depending on the static stability of the atmosphere, being rigorous for stability class 2 and not very important for class 4. At night, vertical mixing is severely limited, and pollutants are transported across long distances most of the time, concentrations decreasing only slowly. Dilution is therefore not a function of distance within the area relevant for such an investigation (about 500 m from the source). Forecasting concentrations at night by a simple model like the Gauss model imposes a lot of uncertainties, because a steady state as required by the model will not be achieved in reality in most cases. Phenomena occurring at night like wind shear, low-level jets or gravity waves cannot be treated by the Gaussian model. Recently, the regulatory model has been evaluated with international data sets (Pechinger and Petz, 1995), whereby rather good results have been achieved for daytime conditions.

The regulatory model calculates half-hour mean concentrations. The sensation of odour, however, depends on the momentary odour concentration and not on a mean value over a long time of integration. The peak-to-mean ratios used here are stability-dependant (Smith, 1973). They are of a similar range as those given by Briggs (1973) and EPRI (1981) with the exponent u (Eq. (4)) ranging between 0.12 and 0.86 (0.5 on average). Short-term peak values can reach up to ten times the half-hour mean value. The German TA-Luft (Jost, 1997) recommends a peak-to-mean ratio of 10 as an upper limit.

The problem of odour regulation is summarized by Nicell (1994) discussing the whole chain of odour sensation (detection 1 OU m^{-3}), discrimination (3 OU m^{-3}), unmistakable perception (5 OU m^{-3}, complaint level), and as a last step the degree of annoyance. The importance of hedonistic effects of odours is shown by comparing the assessment of odour intensity with the odour concentration: pleasant odours are more favourably assessed than unpleasant ones even if concentrations are equal (Hangartner, 1988 and 1990; Paduch, 1988). Bundy et al. (1997) showed that by selecting a power law the intensity of odour of pigs can be described by the odour concentration with an exponent in the range of 0.52–0.71. The relationship between odour concentration and the degree of annoyance seems to be weak in general because a covariance of only 10–20% is reported by Pulles and Cavalini (1990).

On the other hand not only the odour concentration and the hedonic character of the odour is important but also the persistance of odour sensation. Winneke et al (1990) give an exceeding probability of 3 to 5% of the year for an average sensitive person. In Germany the exceeding probability depends on the land use category. Besides the exceeding probability, also the odour concentration is relevant for this assessment. The following limits are in use in Germany: For pure residential areas the exceeding probability has to be lower than 3% and 1 OU m^{-3}, residential and structured areas 5% and 1 OU m^{-3}, restricted business areas and village area with mixed utilisation 8% and 1 OU m or 3% and 3 OU m, and village-areas with predominantly agricultural utilisation 10% and 1 OU m or 5% and 3 OU m (Knauer, 1994; Kypke, 1994). The limits used in the UK are summarized in Table 5.

The model calculation showed that the shape (exponent b) of the separation curve is independent of the selected exceeding probability (Table 4). This means that the different limits of the exceeding probability of odour concentration due to different land use categories can be taken into account by changing the multiplier of the power function (factor a) as it is done by the guidelines (Schauberger and Piringer, 1997a, b). The increase of the goodness of the fit with increasing exceeding probability can be explained by the fact that the uncertainty of the fit increases towards the tails of the fitted function (Fig. 2).

Until now no suitable model is available in order to assess the annoyance by odour from the odour concentration and the persistence of the odour sensation. The evaluation of the guidelines done in this paper was based on the maximum odour concentration. Under the assumption that the ratio between the calculated odour

Table 5
Limits of odour concentration and exceeding probability used in the UK (Hobson, 1997). The dilution factor was calculated assuming an odour emission concentration of 500 OU m^{-3}

Receptor concentration (OU m^{-3})	Calculated dilution factor for an odour emission concentration of 500 OU m^{-3}	Percentile compliance: exceeding probability for a certain receptor concentration p (‰)	Remarks
10	50	20 (175 h/a)	Serious annoyance expected with near certainty
1–5	500–100	20 (175 h/a)	Generally acceptable for existing installations. Emissions from stacks or large area sources may be acceptable at the relaxed end of the range
<1	>500	20 (175 h/a)	No serious annoyance expected in the large majority of cases
1	500	5 (44 h/a)	Safe target value for new sources
10	50	0.1 (0.9 h/a)	Applicable to highly intermittent sources

concentration by the Gauss model and the annoying level is constant, the results of the model calculation can be used as relative values.

The results obtained in this study concerning the dependence of the separation distance from the odour emission of livestock farms cannot be generalized for the reasons stated above. They suggest, however, that the current regulations for calculating separation distances should be modified. A more thorough investigation including a sensitivity analysis with respect to meteorological parameters or source configurations seems necessary before proposals for such modifications can be done seriously. Such investigations will be undertaken in Austria in the near future.

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