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ORIGINAL PAPER

A level of service scheme for microscopic simulation of pedestrians that integrates queuing, uni-and multi-directional flow situations

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Abstract The concept of Level of Service is widely used in road traffic planning as well as in planning for pedestrian traffic and events. Pedestrian Level of Service schemes either are based on density alone or on special elements that are situation dependent (like width of sidewalks). In this contribution an extension of the original density-based Level of Service schemes is suggested for use in microscopic simulation of pedestrian traffic. The proposed concept does with only one scheme, i.e. with only one set of level breakpoints for different situations as queuing, uni-directional, bi-directional, or multi-directional flows. The level breakpoints of the proposed concept can be calibrated to existing sets of Level of Service schemes. In this way applicants can continue to rely on their experience with the established concepts.

Keywords Level of service · Pedestrians · Simulation · Bi-directional flows · Multi-directional flows

1 Introduction

1.1 Motivation and outline

"Level of Service" (LOS) in transportation science is a concept to break the continuous range of traffic-state dependent quality and availability of traffic infrastructure into a manageable number of (mostly six) levels. Often the properties of the levels are described in a few graphic phrases, catching what is happening in a situation with a particular LOS value.

Traffic planning and traffic engineering in terms of cost and material moved to build the infrastructure is mainly planning and engineering for vehicular traffic. Therefore the most prominent LOS scheme is one for highway traffic given in the Highway Capacity Manual [1]. However, there is no reason, why the concept should not be used for pedestrian planning as well. In deed there is as well almost a plethora of LOS schemes for pedestrian traffic. Examples are shown in Fig. 1.

In classic assessment of traffic infrastructure an area statically has been assigned to a predominant way of usage. From the predominant usage followed the type of LOS scheme that is to be used for assessment, i.e. "walkway" LOS scheme, "queuing area" LOS scheme, "bi-directional walkway" LOS scheme, "crossing" LOS scheme. However, reality can be more dynamic. The way an area is used can change in a matter of hours, minutes or even seconds. This can be modeled with microscopic simulations.

What is missing up to now is a LOS scheme that is as dynamic as a microscopic simulation. Such a dynamic LOS scheme should automatically give the right experienced LOS value when an area is used as queuing area and if the queue dissolves it should give the right experienced LOS value some minutes later, when the same area is used as walking area. There should be no need for a planner to configure time intervals to use different LOS schemes that accommodate for the different usage. This is not just a matter of comfort for a modeler. Most models of pedestrian dynamics are

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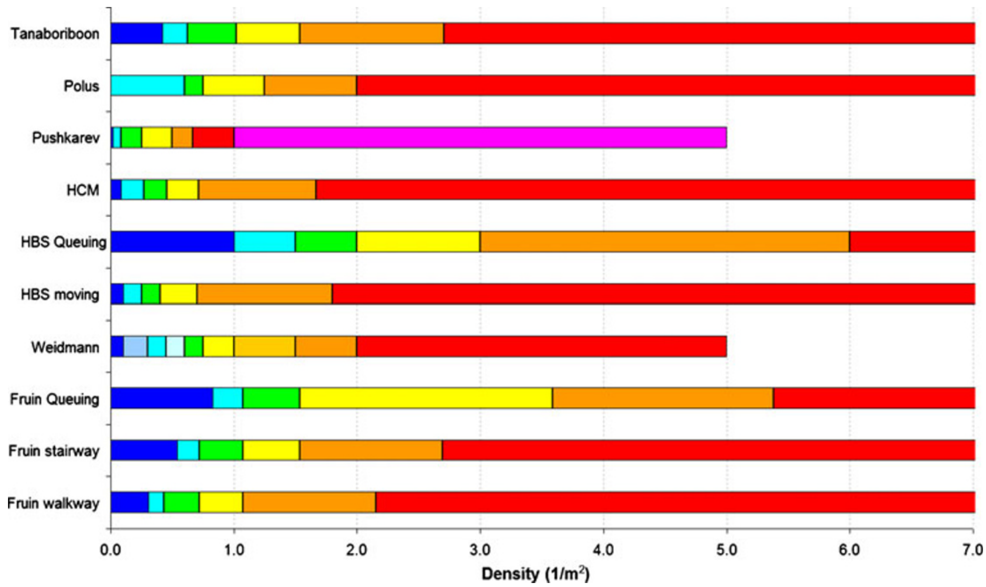

Fig. 1 A selection of various existing exclusively density-based level of service schemes. Most relevant for this work are the walking and queuing schemes according to Fruin, HBS, and HCM

stochastic. Different simulation runs may give (slightly) different points in time when the usage of an area changes. Therefore—even if a planner was willing to do the effort of configuring time intervals of LOS scheme application—there is in general no way to define these time intervals with general validity.

One solution of this problem would be that the walking situation is analyzed by the software in which the pedestrian dynamics model is implemented and a usage type is calculated from which the software automatically chooses an adequate out of a set of LOS schemes for particular purpose. This approach is not followed here further. Instead the idea of this contribution is to have one single LOS scheme in which the calculation of the levels rests on a set of properties of the system dynamics. Compared to the situation analysis approach the difference is that there is a continuous transition between distinct LOS scheme for "pure" situations like queuing, uni-directional flow or 50:50 bi-directional flow. It offers a way to also assess for example crossing flows with a few main and many secondary directions at arbitrary angles.

The paper is organized as follows: the remainder of the introduction gives an overview of existing LOS schemes and discusses differences between vehicular and pedestrian traffic which are relevant for the topic of the paper. Then the equation for the proposed LOS scheme is defined, next the motivation for its form follows straight after. Finally the parameters are calculated such that the new LOS is as far as possible in agreement with established LOS schemes.

1.2 Overview of existing pedestrian level of service schemes

One of the earliest LOS schemes for pedestrian traffic is the one by Oeding [2], however, the most influential surely was proposed by Fruin [3] as it caused that a pedestrian LOS scheme was integrated to the Highway Capacity Manual (HCM) [1]. The German "Handbuch für die Bemessung von Straßenverkehrsanlagen" (HBS) includes a scheme with very similar breakpoints as in the HCM [4]. Polus et al introduced a LOS scheme based on empirical observations in Israel [5]. Weidmann reviewed a number of prior schemes and suggested a LOS scheme with eight but six levels, so he could reuse roughly the level breakpoints of various other schemes [6, 7]. Tanaboriboon and Guyano intended to create an Asian LOS scheme [8] and studied pedestrian parameters in Bangkok.

All these schemes are based on density only. Fruin, however, gave an alternative formulation by giving the level breakpoints in flow rates (implying equivalence between both) and Teknomo proposed a speed-based LOS scheme ("the faster the better") [9]. The Florida Department of Transport followed another approach and defined a LOS scheme for the specific purpose of planning for pedestrians as participants of street traffic [10, 11]. The New York City Department of City Planning conducted (and is still conducting) another large scale study on the quality and LOS for pedestrian walking [12]. Another relevant document was published by Land Transport New Zealand [13].

1.3 Consequences of differences between vehicles and pedestrians for the level of service concept

Pedestrians are different from vehicles in a number of properties: they are smaller, they are slower, they reach their maximum speed much quicker, etc. But the differences relevant for the LOS concept are that first off, pedestrians can and do move freely in two spatial dimensions and pedestrians change their shape with speed, i.e. they have a larger step size, cover more ground area, they need more space, when they walk faster. A car could push another (passive) car immediately in front of it. A pedestrian could not do so, except by throwing the other over. The pedestrian in front would at least have to lift the same leg as the pushing pedestrian, else the pushing pedestrian can not create a locomotion, as he would lack the space necessary to do so.

The first difference between vehicles and pedestrians gives rise to various kinds of flow relations: all pedestrians of some proximity can move into almost the same direction, two groups might meet in a counterflow or crossing flow situation. Walking pedestrians might have to cross an area with dwelling pedestrians on it. One can even think of situations with almost equally distributed walking speeds with everyone hustling at what ever speed allowed by traffic conditions or personal fitness into arbitrary directions; a station hall might provide a situation closest to this.

This first difference has been taken account for by existing LOS schemes by defining different schemes (different sets of level breakpoints) for walkways and queuing situations [1, 3, 4] and correction factors for densities in counterflow situations to apply a walkway LOS to the corrected densities [4].

The second difference between vehicles and pedestrians—changed shape when moving—at first sight is a similarity: for higher speeds, larger headways are required. The difference is that for vehicles this is exclusively from the fact that a constant reaction time requires larger headways at higher speeds to avoid collisions. This phenomenon exists also with pedestrians. However, for pedestrians in addition there is the fact that the step size increases with higher speeds and with this the occupied space increases. With a density definition as from Predtechenskii and Milinski ([m^2/m^2]) this implies an increased effective density.

This means that for pedestrians there are two effects which imply that the effective dynamic length is increased: one as a consequence of reaction time and one from the way pedestrian locomotion is done. It is not yet clear, if these two effects add to each other or if one is included in the other. For example the headway necessary to avoid collisions could always be smaller than the step length or vice versa, or the former could be the case at lower and the opposite at higher speeds. What is clear is that visible on still images and therefore directly measurable on still images is only the step length.

2 Equation of the proposed LOS scheme

The remainder of the paper is easier to read, if here the scheme is summarized and the equation for the LOS calculation is given. In its most aggregate form it is:

$$M = \rho + \frac{\bar{j}}{c_1} + \frac{P}{c_2^2} \tag{1}$$

which reads as "The quantity of interest M is the sum of first: number density of pedestrians, second: a flow-like value over some speed constant c_1, and third: crowd pressure over the square of a second speed constant c_2".

What cannot be seen in this equation, only in the next one is that the idea is to use an existing LOS scheme for queuing situations, and multiply the density with a factor composed of dynamic measurable quantities ("observables") of the traffic state. This factor is made sure to be 1 for queuing pedestrians standing still and larger 1 for any other situation. The size of the factor should be such, that about the same levels result, as if one would work with a LOS for walkways and a LOS for queuing areas and a LOS for counterflow situations if the observables have values that are typical for such situations.

This might become clearer, if one separates in Eq. 1 the density from the rest:

$$M = \rho \left(1 + \frac{\bar{v}}{c_1} + \frac{\mathrm{VAR}(\mathbf{v})}{c_2^2}\right) \tag{2}$$

which reads like: "The correction factor, to multiply the number density with, is one plus the average speed over some speed constant c_1 plus speed variance over the square of another speed constant c_2".

The resulting parameter M is the one, which determines the LOS. This means that the level breakpoints are defined with respect to the value of parameter M.

$\bar{v}$ is the average of the absolute values of the speed:

$$\bar{v} := \frac{1}{N} \sum_{i=1}^{N} |v_i| \tag{3}$$

with N as the number of pedestrians located on the area for which the LOS is to be calculated.[1]

The variance of velocities VAR($\mathbf{v}$) is defined as:

$$\mathrm{VAR}(\mathbf{v}) = \frac{1}{N}\sum_{i=1}^{N}(\mathbf{v}_i - \bar{\mathbf{v}})^2 = \frac{1}{N}\sum_{i=1}^{N}\left(\mathbf{v}_i - \frac{1}{N}\sum_{j=1}^{N}\mathbf{v}_j\right)^2. \tag{4}$$

Note that it is the variance of the vector-valued velocities, not the variance of the absolute values, the speeds.

3 Motivation of Eq. 1

With the intention stated in the introduction to formulate a LOS scheme that integrates various situations of pedestrian dynamics, it is clear that the equation needs to involve observables that discriminate between the movement situations for which the LOS scheme should be applicable. The movement situations were mentioned to be queuing and movement in all possible relative directions. Therefore the average speed has been chosen as observable to distinguish queuing from movement, and the variance of velocities to distinguish uni- from multi-directional movement.

At this state Eq. 2 has the much more unspecified form of

$$M = \mathrm{func}\,(\rho, \bar{v}, \mathrm{VAR}\,(\mathbf{v})) \tag{5}$$

namely that M is some function of the observables density ρ, average speed $\bar{v}$, and variance of velocities VAR($\mathbf{v}$). By comparison with existing LOS schemes, it becomes apparent that the function must depend linearly on the density. As with smaller densities the average speed increases, but M should keep approaching zero, when density does so, and as for queuing situations everything should reduce to $M = \rho$, Eq. 5 takes a more special form:

$$M = \rho \cdot (1 + \mathrm{func}\,(\bar{v}, \mathrm{VAR}\,(\mathbf{v}))) . \tag{6}$$

with the restriction that the function should vanish when the average speed approaches zero as in a queuing situation.

The simplest argument how to proceed from this equation to Eq. 2 is that Eq. 2 constitutes the simplest non-trivial of all possible equations in agreement with Eq. 6. Furthermore the products of the density with the average speed and the variance of velocities respectively as properties are used in traffic planning and theory and therefore have a meaning of their own as net specific flow and crowd pressure. Therefore Eq. 1 should be a good starting point to work with, later refinements not excluded, provided the experience with Eq. 1 suggests refinements.

The preceding paragraph is made up of hand waving arguments to motivate Eq. 1. To line this, the next two subsection discuss both of the additional terms more closely.

3.1 Specific flow term

In literature one finds that the step size l_{dyn}—in a certain range of speeds—increases linearly with speed v as well as that there is a linear relation between available headway and chosen or possible walking speed. In general:

$$l_{\mathrm{dyn}} = l_{\mathrm{stat}} + mv \tag{7}$$

with the body diameter at rest ("length") of l_{stat}. Weidmann for example cites Margaria and gives for the *step size s* in dependence of the walking speed v: $s = 0.235$ m + 0.302 s v [6, 14]. Seyfried et al. depending on the population and situation find for the *headway* (note the difference to Weidmann) of single file movement 0.36 m + 1.06 s v, 0.36 m + 0.56 s v, 0.36 m + 1.04 s v, 0.22 m + 0.89 s v, and 0.25 m + 0.88 s v [15–17].

Table 1 summarizes the values the existing literature offers as combinations for the averages of the parameters $\bar{l}_{\mathrm{stat}}$ and m, either for step size or for headway.

This is important, as it increases the effective length and therefore density of the pedestrians. With step size, the effective width increases physically (Predtechenskii and Milinski give densities only as ratio of covered area [m^2/m^2]) and the headway can be seen as increasing the effective density psychologically (the area covered by pedestrians AND headway area rises with the velocity).

It is assumed for now that the width of a pedestrian does not depend on the speed, neither physically nor psychologically in its effect on other pedestrians. It is

Table 1 Literature value combinations for $\bar{l}_{\mathrm{stat}}$ and m

$\bar{l}_{\mathrm{stat}}$ (m)	m (s)
0.235	0.302
0.36	1.06
0.36	0.56
0.36	1.04
0.22	0.89
0.25	0.88

[1] We will restrict the discussion here on the calculation of a LOS for an area. At the end of the paper it is shortly considered, how a perceived LOS for an individual pedestrian could be done and the difficulties one is faced with if one intends to do so.

known that the body sway is larger at lower speeds, but the functional form is not yet clear, especially concerning the psychological effects. Even if there is a dependence of the effective width on speed, this assumption can be justified, if the contribution to the additionally occupied area at higher speed comes mainly from a dynamic increase of the effective length into the walking direction compared to a growth orthogonal to it.

For this reason as a first step a "dynamic density" is calculated from the static (normal) one by (with length l and width w, and the parameters b and m being intercept and slope of the linear dependence of step size of width as given above)

$$\rho_{\text{dyn}} = \rho_{\text{stat}} \frac{\bar{A}_{\text{dyn}}}{\bar{A}_{\text{stat}}} \tag{8}$$

$$= \rho_{\text{stat}} \frac{\bar{w}_{\text{dyn}} \bar{l}_{\text{dyn}}}{\bar{w}_{\text{stat}} \bar{l}_{\text{stat}}} \tag{9}$$

$$= \rho_{\text{stat}} \frac{\bar{l}_{\text{dyn}}}{\bar{l}_{\text{stat}}} \tag{10}$$

$$= \rho_{\text{stat}} \frac{\bar{l}_{\text{dyn}} + m\bar{v}}{\bar{l}_{\text{dyn}}} \tag{11}$$

$$= \rho_{\text{stat}} \left(1 + \frac{\bar{v}}{\bar{l}_{\text{dyn}}/m}\right) \tag{12}$$

$$= \rho_{\text{stat}} \left(1 + \frac{\bar{v}}{c_1}\right) \tag{13}$$

The assumption that the width does not depend on the walking speed is already used when transforming Eqs. 8 and 9, as the average of a product is not necessarily the product of its averaged factors. From Eqs. 9 and 10 this is used to cancel w.

Equation 13 reveals that the first additional term of Eq. 2 is equivalent with the assumption of a linear dependence between speed and headway or step size respectively. If this is not fulfilled, corrections might be necessary. Equation 1 already contains a correction term, namely the pressure term. This can be seen as taking into account that for pedestrians in general—i.e. if they are not moving single-file—a headway cannot be defined rigorously and the possibility of crossing and opposing pedestrians can lead to a perception of the LOS where higher speeds have a worse impact than entering the equation linearly in the given way.

For the sake of completeness, it should be noted that there can well be other reasons for modifications, for example if there is some other dependence than a linear one for very small or very high speeds.

The constant c_1 could in principle be calculated as $c_1 = \bar{l}_{\text{dyn}}/m$, but after having arrived at Eq. 13 and bearing the pressure term in mind, one might better generally consider c_1 to be a gauge constant to be set to meet some specific purpose—namely to calibrate the proposed LOS scheme to give results close to existing LOS scheme sets—than to assume it can be derived from empirical data. However, if one chooses to calculate c_1 in this way, it is probably better to not use the values from step size but from the measured headways, as the step size increase is smaller and therefore included in the headway from reaction time. Then it must be kept in mind that these numbers stem from single-file movement experiments, while the LOS scheme is intended to be applied to pedestrian dynamics in general.

3.2 Pressure term

In some dynamic continuum models of traffic flow the quantity "traffic pressure" is made use of (see for example the overviews [18, 19]) and is defined as in gas-kinetic theory as

$$P = \rho\Theta. \tag{14}$$

With density ρ and Θ the variance of speeds on some part of the highway.[2]

Johansson et al. transfered traffic pressure to crowd pressure and by this to two dimensions to make use of the concept for safety analyses in Makkah [20, 21]. They show that crowd pressure can be used to estimate, if the state of a crowd gets critically close to a collapse.

With the general properties of the variance and the record of usage of pressure defined in this way, crowd pressure appears to be helpful for usage in the intended LOS calculation. And hence we arrive at the initially stated Eqs. 1 and 2.

These equations allow for the daily experience that at a given density it feels as a worse LOS, when everyone is walking in different directions, than when everyone is walking at identical speed into the same direction and that it feels as a worse LOS if everyone is walking with same speed and direction than when everyone is standing still and that a higher density generally feels as a worse LOS. With a c_2 chosen sufficiently small,

[2]Note that "Pressure" as used in traffic theory must not be confused with an experienced physical pressure (force over area) on an individual in a crowd. The relation between both pressures is that if the vehicles were gas particles and if a box was comoving with a part of the highway at the average speed of the vehicles in the box, the gas-kinetic pressure would in a *long-term average* equal the experienced pressure on the front and end side of the box. Or it would equal the experienced pressure, if there were billions such highway lanes next to each other and above and beyond and all covered within the same box.

Helbing's observed increase of crowd pressure, could lift M to values that could never be reached by density alone.

The reason to use a sum of density and pressure is that on the one hand today all well acknowledged LOS schemes are based on density and Helbing et al claim that pressure is a good measurement to predict crowd collapses.

Crowd collapses only can occur during situations of high density, so one does not have to think if pressure alone is a good measure to assess far lower densities as traffic planers have to deal with. So, the assumption is that in everyday situations crowd density is an important measure to assess the walking situation quality (this is the former summand), but that it's important for the experienced stress level, if at a given density everyone is walking in one direction, in two directions or criss-cross; and exactly for this the second summand, the pressure can be a measure for. The second summand alone would not be sufficient, as it would vanish if all pedestrians in a dense flow have the same velocity (walk with identical speed into the same direction). This, however, does not correspond to the experience, that something like this would not feel like LOS A.

An objection against the proposed LOS scheme might lie with the role speed plays: why should the LOS worsen, if the speed is increased? Normally "faster is better" and if one has a LOS scheme that is exclusively based on speed, the best LOS is achieved at high speeds [9]. But there's a fundamental difference between a LOS scheme that rests exclusively on speed and the proposed LOS scheme. If one only looks at the speed, one can forget about the empirical relation of speed and density. In Eq. 1, however, speed and density are linked. Higher speeds can only be achieved at lower densities. By multiplying both one has the specific flow. Fruin gives the level breakpoints alternatively as specific flow volumes, also with "higher is worse" for the LOS value. To compensate for the generally higher values of M, as one sums up density and low, one will have to use higher numbers for the level breakpoints based on M than those of the standard LOS schemes.

4 Fixing the values of c_1 and c_2

The constants c_1 and c_2 in principle are free parameters that can be set in an arbitrary way. The following calculations therefore just make a suggestion and try to give a feeling on the order of magnitude to what value they should be set.

Fruin, the HCM, as well as the HBS include LOS schemes for walkways (for one-directional flows!) as well as queuing areas. The HBS gives factors to take into account counterflows, not directly for level breakpoints but for the flow volumes. The idea now is to use the level breakpoints of an established queuing area scheme as breakpoints to apply with M (if no one moves, $M = \rho$) and fix the constants such that the dynamics increase M at the density of the level breakpoint from A to B of the walkway scheme to the density of the breakpoint from A to B of the queuing area scheme. The breakpoint from A to B is chosen, as one needs to know the variance of velocities. It is assumed here that at the level breakpoint from A to B the actual speed is very close to the desired (free) speed and one can calculate the variance value of speeds as the variance value of a distribution of desired (free) speeds.

Let us look at three situations: (1) a group of pedestrians is queuing with density ρ^q_{AB}, which is the density of the A→B breakpoint for queuing areas; (2) a group of pedestrians is walking into the same direction with a speed distribution $g(v)$ at density ρ^w_{AB}, which is the density of the A→B breakpoint for one-way walkways; (3) a group of pedestrians is walking 50:50% bidirectional with the same distribution of desired speeds $g(v)$ at density ρ^c_{AB}, which is the density of the A↔B breakpoint for counterflow walkways. This means that while in the second case the average velocity is $\bar{v} > 0$ it vanishes in the third case, the average speed, however, does not vanish and due to the low density is about the same as for the second case: $\bar{v} = |\bar{v}|$ (calculated from the distribution of desired speeds).

This leads to these two equations:

$$\rho^q_{AB} = \rho^w_{AB}\left(1 + \frac{\bar{v}}{c_1} + \frac{\overline{v^2} - \bar{v}^2}{c_2^2}\right) \tag{15}$$

$$\rho^q_{AB} = \rho^c_{AB}\left(1 + \frac{\bar{v}}{c_1} + \frac{\overline{v^2}}{c_2^2}\right) \tag{16}$$

In the second equation the average of velocities is (except for fluctuations to to the limited sample size) zero in 50:50% counterflow and is therefore omitted.

This can easily be solved for an equation for c_2:

$$c_2^2 = \bar{v}^2 \frac{\rho^w_{AB}\rho^c_{AB}}{\left(\rho^w_{AB} - \rho^c_{AB}\right)\rho^q_{AB}} = \bar{v}^2 \frac{\rho^w_{AB}\rho^c_{AB}}{\left(\rho^w_{AB} - \rho^c_{AB}\right)\rho^q_{AB}} \tag{17}$$

The square of average of velocities here is the one of uni-directional flow and is therefore identical to the square of average of speeds.

In the HBS there is a factor given (called f_c in this paper) to take counterflows into account by scaling larger the actual density, if one is faced with a counterflow situation. Here this means that—as in a counterflow situation the correction factor is larger than for uni-directional flow—the same value of M is reached for counterflow situations at lower densities than for uni-directional flow. And hence one can replace

$$\rho^c_{AB} \rightarrow \frac{\rho^w_{AB}}{f_c} \tag{18}$$

in Eq. 17, which then reads

$$c_2^2 = \bar{v}^2 \frac{\rho^w_{AB}}{(f_c - 1)\,\rho^q_{AB}} \tag{19}$$

When counterflow is seen to bring a LOS as one-way traffic with a 5% higher density one has $f_c = 1.05$.

With the values from HBS and an average desired speed of 1.5 m/s one has $c_2 = 2.12$ m/s. Inserting Eqs. 19 into 16 and solving for c_1 results in

$$c_1 = \frac{\bar{v}}{f_c \frac{\rho^q_{AB}}{\rho^w_{AB}} - 1 - (f_c - 1)\frac{\overline{v^2}}{\bar{v}^2}\frac{\rho^q_{AB}}{\rho^w_{AB}}} \tag{20}$$

With $\rho^q_{AB} = 1.0/\text{m}^2$, $\rho^w_{AB} = 0.1/\text{m}^2$, $f_c = 1.05$, and desired speeds equally distributed between 1.0 and 2.0 m/s (a rather large scatter) one has $c_1 = 0.167$ m/s.

Calculating c_1 from the data of Table 1 ($c_1 = \bar{l}_{\text{stat}}/\text{m}$) results in values between 0.25 and 0.78 m/s. This matches well with the range of values calculated in Table 2. That there is such a wide range of results with this way to calculate c_1 may be due to the interrelation of headway and step size discussed as "second difference" in Section 1.3.

Just as the many LOS schemes are varying in their level breakpoints the constants c_1 and c_2 vary, if one calculates them based on different existing LOS schemes. Table 2 lists a few.

There is a third way to calculate c_1, at least, if—as Fruin did—the level breakpoints are not only given as densities, but also as flow rates, or if a researcher has published a LOS scheme (for queuing areas and walkways) and a fundamental diagram.

For one-directional flow, the crowd pressure becomes small, as the variance of velocities is small. Then Eq. 1 becomes

$$M = \rho + \frac{\bar{j}}{c_1} \tag{21}$$

One then can calculate c_1 from

$$\rho^q_{AB} = \rho^w_{AB} + \frac{\bar{j}^w_{AB}}{c_1} \tag{22}$$

which is

$$c_1 = \frac{j^w_{AB}}{\rho^q_{AB} - \rho^w_{AB}} \tag{23}$$

Table 2 c_1 and c_2 from different LOS schemes and speed distributions (equal distributions between min and max, except for the lines with v between 0.71 and 1.62 m/s, where an equal mixture of 30–50 year old women and men was assumed with walking speeds according to [22]); densities in [1/m^2] and speeds in [m/s]

	ρ^w_{AB}	ρ^q_{AB}	f_c	$v_{\min}$	$v_{\max}$	c_1	c_2
HBS	0.10	1.00	1.05	1.00	2.00	0.17	2.12
			1.05	1.40	1.60	0.17	2.12
			1.05	1.00	1.60	0.14	1.84
			1.05	1.20	1.40	0.14	1.84
			1.05	0.71	1.62	0.13	1.59
			1.10	1.00	2.00	0.17	1.50
			1.01	1.00	2.00	0.17	4.74
Fruin	0.31	0.83	1.05	1.00	2.00	0.89	4.09
			1.05	1.40	1.60	0.89	4.09
			1.05	1.00	1.60	0.77	3.54
			1.05	1.20	1.40	0.77	3.54
			1.05	0.71	1.62	0.67	3.06
			1.10	1.00	2.00	0.89	2.89
			1.01	1.00	2.00	0.89	9.14
HCM	0.18	0.83	1.05	1.00	2.00	0.41	3.11
			1.05	1.40	1.60	0.41	3.11
			1.05	1.00	1.60	0.36	2.69
			1.05	1.20	1.40	0.35	2.69
			1.05	0.71	1.62	0.31	2.33
			1.10	1.00	2.00	0.41	2.20
			1.01	1.00	2.00	0.41	6.95

and receives for Fruin $c_1 = 0.735$ m/s. This value is smaller than the values of Table 2 (just considering those based on Fruin's LOS schemes) as we have neglected the crowd pressure. With typical values for the crowd pressure (at that density) for one-directional flow and typical values for c_2, c_1 increases by some 0.01 m/s.

For these calculations a number of assumptions have been made, as that at the level breakpoint A to B the walking speeds are the free speeds and that the average velocity is exactly zero in 50:50% counterflow situations. Therefore and for the wide scattering of the calculated values, these values can only be a starting point and fine tuning has to be done by applying the proposed scheme.

5 Example

As an example we calculate the area-based M values for pedestrians walking one-directional, two-directional, and crossing orthogonally. For this we use the values of the first line of Table 2 (i.e. this example is based on HBS), except for a density of 0.2/m^2. This is more than the level breakpoint between A and B, but according to most fundamental diagrams it is still free flow ($v/v_0 > 0.99$). Let us neglect all deviations from the main direction and fluctuations with time (i.e. use long-term averages, resp. the average of the given distribution) and also that the walking speed might be slower in walking situations other than one-dimensional.

For queuing pedestrians there is trivially $M = 0.2/\mathrm{m}^2$.

For one-directional flow the average velocity is the average speed into the walking direction and therefore the variance is $\overline{v^2} - \overline{v}^2 = 0.083$ m/s and therefore $M = 0.2(1 + 1.5/0.17 + 0.083/2.12)/\mathrm{m}^2 = 1.97/\mathrm{m}^2$.

For two-directional flow (opposing flows) the average velocity vanishes (but not the average speed) and therefore the variance is $\overline{v^2} = 2.333$ m/s and therefore $M = 0.2(1 + 1.5/0.17 + 2.333/2.12)/\mathrm{m}^2 = 2.18/\mathrm{m}^2$.

For crossing flows the average velocity points into the "average direction" with an absolute value of $\overline{v_0}/\sqrt{2}$. The variance then is $\overline{v^2} - \overline{v}^2/2 = 1.208$ m/s and therefore $M = 0.2(1 + 1.5/0.17 + 1.208/2.12)/\mathrm{m}^2 = 2.08/\mathrm{m}^2$.

In result for queuing pedestrians (at rest) level A (in HBS up to $1/\mathrm{m}^2$) is shown for the area, for one-directional flow it is level C (in HBS up to $2/\mathrm{m}^2$) and for the other two situations level D (in HBS up to $3/\mathrm{m}^2$).

It might be argued that for walkways this density in HBS is part of LOS B. The discrepancy mainly results from the large range the quotients of level breakpoints (breakpoint values for queuing over walkways) have in the HBS LOS scheme, namely between 3.3 and 10.0 compared to 3.7–4.7 in HCM and 2.1–3.3 in Fruin's schemes. As only the breakpoints A→B are used to calculate the parameters, such discrepancies must occur, if the quotients are very different for other breakpoints. The LOS scheme proposed in this paper is not able to reproduce sets of LOS schemes exactly, where the quotients of the density values of associated level breakpoints vary so strongly. This could be fixed by modifying Eq. 1 by applying powers different from 1 to the second and third summand and thus make the dynamic LOS scheme exactly reproduce the three static ones for "pure" situations. As this would add two extra parameters (the powers) to the scheme, it is argued to interpret the computation of c_1 and c_2 from the breakpoints of specific sets of schemes rather as a loose motivation than a strict derivation from which one can expect strict agreement of results.

6 Outlook: an individual-based LOS scheme

In the sums to calculate the density, the average speed, and the variance of velocities all summands had a weight factor of 1, if the corresponding pedestrian is located on the area for which the LOS value is to be calculated. All pedestrians not located on that particular area were not considered. That is why the calculation was called "area-based".

It would be interesting to calculate a spot-based or an individual-based LOS value. Imagine a 90:10% counterflow situations. There the experienced LOS value is surely worse for members of the minority group than for members of the majority group (Fig. 2 gives an

Fig. 2 Illustration of combined application of area-based and individual-based LOS value calculation. The pedestrians of the main walking direction experience a better LOS value (displayed as *green* and *yellow-green shirts*) than is measured on the area (*yellow*) which itself is a better LOS value than the one experienced by the pedestrians of the minor (opposing) group (displayed as *orange* and *red shirts*). This illustration was made using VISSIM [26]

illustration of this idea). Even for 50:50% counterflow situations there can be different experienced LOS values, depending on the number of lanes on the area for which the LOS is of interest. The area-based LOS scheme which has been proposed in this paper is blind to the number of lanes.

With Voronoi diagrams [23, 24] it is possible to calculate an individual density for a particular pedestrian and dynamically determine, which neighboring agents are taken into the sum for average speed and variance of velocities.

A second bunch of methods that uses distance-dependent weights to calculate the density [20, 21, 25] is available. With these (and a large number of variants) it is possible to take an arbitrarily large environment into account for the calculation of all the quantities in question. The downside of this is that with any of these methods new degrees of freedom in form of additional parameters come into play, which makes it even more difficult to calibrate these methods such that they lean to existing LOS schemes.

Working out the details of how to use one of these methods or even combining some of them would blow up the extend of this paper and blur the focus of this paper which is on Eq. 1 and not on formulating an individual-based LOS scheme. Strictly speaking this is another tasks, unrelated to the one proposed in this section. However, it is one that suggests itself more with the LOS scheme of this paper because of the calculation of the variance of speeds, where it should be intuitively clear, that it is not only the relative walking orientation of another pedestrian but also how far this pedestrian is away from *me* that contributes to an experienced LOS value.

7 Summary and conclusions

A new LOS scheme for pedestrians has been presented that unifies sets of existing schemes, where each scheme has a narrowly defined scope of application like queuing areas or one-directional flow. It was tried to fit the new scheme by parameter calibration as neatly as possible to existing widely used schemes respectively sets of schemes.

A LOS scheme can only proof its usefulness by being applied, which for the scheme proposed here obviously has not yet been done. The LOS scheme in the HCM has been refined multiple times. If the scheme presented here, proofs to be useful in general, finding the best value—or way to calculate it—for R will take time to compile the experience with the method, necessary to develop a feeling for these parameters. And the same would have to be done for c_1 and c_2, if the proposed method to calculate it does not proof to be useful.

This paper has its focus on the calculation of a LOS value with respect to a certain area (area-based procedure). However, at the end of the paper it is proposed as outlook to extend the scheme to be able to calculate a LOS value as perceived by individuals or at certain spots. The calculations for the parameters c_1 and c_2 were all done with respect to an area-based procedure. It remains to be examined if the parameters for an individual-based procedure can be chosen in a similar manner.

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References

1. TRB (2000) Highway Capacity Manual
2. Oeding D (1963) Straßenbau und Straßenverkehrstechnik 22
3. Fruin J (1971) Pedestrian planning and design (Metropolitan Association of Urban Designers and Environmental Planners)
4. FGSV (2001) Handbuch für die Bemessung von Straßenverkehrsanlagen (HBS). Forschungsgesellschaft für Straßen- und Verkehrswesen, Kommission Bemessung von Straßenverkehrsanlagen, Köln
5. Polus A, Schofer J, Ushpiz A (1983) Pedestrian flow and level of service. J Transp Eng 109:46–56
6. Weidmann U (1993) Transporttechnik der Fußgänger—Transporttechnische Eigenschaften des Fußgängerverkehrs. Schriftenreihe des IVT 90, ETH Zürich. Zweite, ergänzte Auflage (in German)
7. Buchmüller S, Weidmann U (2007) Parameters of pedestrians, pedestrian traffic and walking facilities. Schriftenreihe des IVT 132, ETH Zürich . Note: this is an English summary and update of Weidmann (1993)
8. Tanaboriboon Y, Guyano JA (1991) Analysis of pedestrian movements in Bangkok. Transp Res Rec 1294:52–56
9. Teknomo K (2002) Microscopic Pedestrian Flow Characteristics: development of an image processing data collection and simulation model. Ph.D. thesis, Tohoku University
10. Landis B, Vattikuti V, Ottenberg R, McLeod D, Guttenplan M (2001) Transportation Research Record: Journal of the Transportation Research Board 1773:82
11. FDoT (2009) Quality/level of service—handbook. State of Florida—Department of Transportation
12. NYCDoCP (2006) New York City Pedestrian Level of Service Study—Phase I. New York City Department of City Planning
13. LTNZ (2007) Pedestrian planning and design guide. Land Transport, New Zealand
14. Margaria R (1976) Biomechanics and energetics of muscular exercise. Oxford University Press

15. Seyfried A, Steffen B, Klingsch W, Boltes M (2005) The fundamental diagram of pedestrian movement revisited. Journal of Statistical Mechanics: Theory and Experiment 2005:10002
16. Seyfried A, Steffen B, Lippert T (2006) Physica A, Statistical Mechanics and its Applications 368(1):232
17. Chattaraj U, Seyfried A, Chakroborty P (2009) Comparison of pedestrian fundamental diagram across cultures. Adv Complex Systems (ACS) 12(03):393–405
18. Hoogendoorn SP, Bovy PHL (2001) State-of-the-art of vehicular traffic flow modelling. Proc Inst Mech Eng, Part I, J Syst Control Eng 215(4):283–303
19. Helbing D (2001) Traffic and related self-driven many-particle systems. Rev Mod Phys 73(4):1067–1141
20. Helbing D, Johansson A, Al-Abideen HZ (2007) Dynamics of crowd disasters: an empirical study. Phys Rev, E 75(4): 46109
21. Johansson A, Helbing D, Al-Abideen HZ, Al-Bosta S (2008) From crowd dynamics to crowd safety: a video-based analysis. Adv Complex Systems 11(4):497–527
22. MSC.1/Circ.1238 (2007) Interim guidelines for evacuation analyses for new and existing passenger ships. Tech. rep., International Maritime Organization, Marine Safety Committee, London
23. Seyfried A, Steffen B (2010) Physica A, Statistical Mechanics and its Applications 389(9):1902
24. Liddle J, Seyfried A, Steffen B (2011) Analysis of bottleneck motion using Voronoi diagrams. In: Peacock R, Kuligowski E, Averill J (eds) Pedestrian and evacuation dynamics, pp 833–836
25. Krauthausen P, Eberhardt H, Hanebeck UD (2010) Multivariate parametric density estimation based on the modified Cramér-von Mises distance. In: Proceedings of the 2010 IEEE international conference on Multisensor Fusion and Integration for intelligent systems (MFI 2010). Salt Lake City, Utah
26. PTV (2010) VISSIM 5.30 User Manual. PTV Planung Transport Verkehr AG, Stumpfstraße 1, D-76131 Karlsruhe, Germany