Evaluation of global comfort for train passengers

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EVALUATION OF GLOBAL COMFORT FOR TRAIN PASSENGERS

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Abstract. The aim of this study is to propose a method for the evaluation of railway passengers' comfort in relationship to temperature, noise, and vibration. Estimated the single comfort for every sensation considered, the global comfort is evaluated with the Hyper-Sphere Method proposed by Corriere & Lo Bosco [1]. The human-vehicle-infrastructure-environment variables which influence comfort are individuated. Thus their value and correspondent global comfort could be evaluated in management strategy or predicted in design problem. The results show how to construct the hyper-sphere in which the surface is representative of best possible condition for human comfort and the centre represents the minimum.

Keywords: thermal comfort, vibration, noise, global comfort, hyper sphere, train passengers, railway.

1. Introduction

The principal goal of this paper is to define an index representative of passenger satisfaction in relation to comfort. The proposed model considers the following three variables: temperature, noise and vibration. These three aspects of comfort have been well documented and analysed in numerous studies.

American Society of Heating, Refrigerating and Air-Conditioning Engineers [2, 3] studied the effects of environmental variables on thermal comfort.

Yang & Kang [4] investigated the acoustic comfort in urban open public spaces, but without finding a good Leq/Comfort-Index correlation coefficient.

Huston, Zhao and Johnson [5] studied the dependency between comfort and vibration frequency/amplitude but they didn't give a method to relate comfort with design variables.

The present study examines how human-vehicle-infrastructure-environment variables produce noise, vibration and condition temperature influencing passenger comfort.

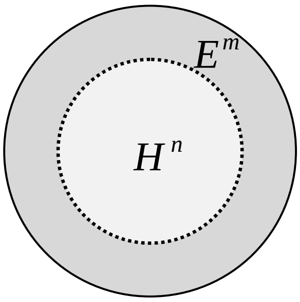
2. Method

Human-vehicle-infrastructure-environment variables are split into two different sets: the "Environment Set (E)" (including vehicle-infrastructure-environment variables) and the "Human Set (H)" (Fig. 1).

The threshold between these sets represents the perceptive organs.

Firstly design variables must be individuated for the chosen parameters aspects of comfort: thermal, noise and vibration.

Then, the relationship functions: temperature/comfort-index, noise/comfort-index and vibration/comfort-index are constructed. For every function and every variable, fixing all variables except one, it's possible to define the superior threshold in relation with maximum comfort while all other variables are fixed at an inferior threshold and vice versa. The $n+m$ variables represent $n+m$ axes of the $\mathbb{R}^{n+m}$ space.



Subsequently all coordinates have been normalised with maximum and minimum threshold calculated by eq. (2).

$$\begin{cases} \varsigma_1 = \frac{\alpha_1 - \alpha_1^i}{\alpha_\Delta}, \dots, \tau_m = \frac{\alpha_m - \alpha_m^i}{\alpha_\Delta} & \alpha_\Delta = (\alpha^s - \alpha^i) \\ \tau_1 = \frac{Z_1 - Z_1^i}{Z_\Delta}, \dots, \tau_n = \frac{Z_n - Z_n^i}{Z_\Delta} & Z_\Delta = (Z^s - Z^i) \end{cases} \quad (2)$$

After this transformation of coordinate, a hyper-sphere (3), in which the surface is representative of best possible condition for human comfort and the centre represents the minimum, is defined:

$$\tau_1^2 + \dots + \tau_n^2 + \varsigma_1^2 + \dots + \varsigma_m^2 \leq 1 \quad (3)$$

Hyper vectors satisfying equation (2) are inside the hyper-sphere and their module represents the Global Comfort Index – $CI \in [0;1]$. Once the global comfort vector is defined, it's possible to evaluate the comfort index to optimize the best management strategy or, in design case, to chose between different planning alternatives. The best solution is the one that maximizes the global comfort vector module.

3. Thermal comfort

The thermal comfort is established by a man-environment energy balance [6] and the equation, for surface area unit, is the following:

$$S = M - W_k - E_{sk} - E_r - C - R - C_k \quad (4)$$

Where S is the instantaneous energy balance of human body (Table 1).

Table 1

Variables introduced in eq. (4)		*Variables introduced in eq. (5)*	
M	metabolic rate	E_{sw}	sweating heat loss
W_k	external work	rh	air relative humidity
E_{sk}	heat loss by evaporation from the skin	t_{mr}	mean radiant temperature
E_r	respiration heat loss, latent and dry	t_{sk}	skin temperature
C	the heat loss by convection from outer surface of the clothed body to air	I_{cl}	clothing, including thermal resistance and vapour permeability
R	the heat loss by radiation from outer surface of the clothed body to its environment		
C_k	heat loss by conduction due to the contact skin/solid object		

For equilibrium and for comfort, S has to result zero. If S results less than zero, the body is releasing more energy than it is producing, consequentially body temperature tends to decrease. Some human-variables in eq. (4) could be written as function of environmental-variables, thus there is equilibrium if (5) is satisfied.

$$f(M, W, I_{cl}, rh, t_{mr}, t_{sk}, E_{sw}) = 0 \tag{5}$$

Furthermore, this equation it's in accordance with Corriere & Lo Bosco [1] theory of comfort-equilibrium (1). Fanger [7] studied a correlation between the mean value of votes given, on a seven-point thermal sensation scale (Table 2), by a large group of people and some environmental and human parameters. Thus he proposed a comfort index called Predicted Mean Vote (6).

$$PMV = (0.303 \cdot e^{-0.036M} + 0.028) \cdot \{(M - W) - 3.05 \cdot 10^{-3}[5733 - 6.99 \cdot (M - W) - p_a] - 0.42[(M - W) - 58.15] - 1.7 \cdot 10^{-5} M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) - 3.96 \cdot 10^{-8} f_{cl} \cdot [(t_{cl} + 273)^4 - (t_{mr} + 273)^4] - f_{cl} h_c \cdot (t_{cl} - t_a)\} \tag{6}$$

Table 2

Variables introduced in eq. (10)		*Thermal sensation scale*		
p_a	partial vapour pressure	+	*3*	Hot
f_{cl}	ratio of man's surface area clothed/nude	+	*2*	Warm
t_a	air temperature	+	*1*	Slightly warm
t_{cl}	surface temperature of clothing		*0*	Neutral
h_c	average skin air convective heat transfer coefficient	-	*1*	Slightly cool
		-	*2*	Cool
		-	*3*	Cold

Normally in a train, during travel, people are seated, so the metabolic rate could be fixed as $M = 58{,}15\ W/m^2$ [6]. Even the external work it's null, so $W_k = 0$. The partial vapour pressure could be calculated with an empiric equation [7]:

$$\begin{cases} P_a = rh \cdot P_s \\ \ln(P_s) = \frac{\alpha_1}{T} + \alpha_2 + \alpha_3 T + \alpha_4 T^2 + \alpha_5 T^3 + \alpha_6 T^4 + \alpha_4 \ln(T) \end{cases} \quad (7)$$

The ratio body surface/clothing can be calculated as follows:

$$f_{cl} = \begin{cases} 1.00 + 1.290 I_{cl} & for\ I_{cl} < 0.078\ m^2\ °C/W \\ 1.05 + 0.645 I_{cl} & for\ I_{cl} > 0.078\ m^2\ °C/W \end{cases} \quad (8)$$

where I_{cl} depends on passenger's clothing, and thus, on season and on external temperature. The average skin air convective heat transfer coefficient:

$$h_c = \begin{cases} 2.38(t_{cl} - t_a)^{0.25} & for\ 2.38(t_{cl} - t_a)^{0.25} > 12.1\sqrt{v_{ar}} \\ 12.1\sqrt{v_{ar}} & for\ 2.38(t_{cl} - t_a)^{0.25} < 12.1\sqrt{v_{ar}} \end{cases} \quad (9)$$

with:

$$v_{ar} = v_a + 0.005\left(\frac{M}{A_{DU}} - 58.15\right) \qquad A_{DU} = 2.02(w_b)^{0.425}(h_b)^{0.725}$$

where V_{ar} is the passenger relative air velocity, V_a is the air velocity, A_{DU} is the body surface calculated by the *Dubois Area* empiric equation. As height and weight of passengers tend to vary on a large range, reference is made to average values (e.g., in Italy, $\overline{h_m} = 1.75\ m$; $\overline{h_w} = 1.65\ m$; $\Rightarrow \bar{h} = 1.70\ m$; $\bar{w} = 75\ kg \Rightarrow A_{DU} = 1.86\ m^2$);
The surface temperature of clothing:

$$t_{cl} = 35.7 - 0.028(M - W) - I_{cl}\{3.96 \cdot 10^{-8} f_{cl}[(t_{cl} + 273)^4 + \\ -(t_{mr} + 273)^4 f_{cl} h_c (t_{cl} - t_a) \quad (10)$$

Air temperature is given by the value set by the regulation of the air conditioning system.
The mean radiant temperature is:

$$t_{mr} = \sum t_i F_{P,i} \quad (11)$$

where t_i is the temperature of the generic isothermal surface-*i* seeing the subject (a wall, a window, a piece of furniture, another person, etc.); $F_{p,i}$ is the view (or angle) factor between the subject-*p* and the surface-*i*.

Once all variables are calculated it is possible to estimate the *Predicted Mean Value* (6).

Finally the aim is to individuate the independent variables which could be controlled or varied in a train design/management problem. Looking at Table 3, these variables are identified with an asterisk (*):

α_1: thermal isolation;
α_2: air conditioning system power (capability to adjust air temperature and relative humidity);
α_3: air velocity;
α_4: mean radiant temperature.

Comfort thresholds recommended by ISO Standard 77302 [8] are $PMV = [-0.5;\ +0.5]$. It's also possible to predict percentage of dissatisfied passengers (*PPD)* with the equation (12).

$$PPD = 100 - 95e^{-(0.03353PMV^4 + 0.21PMV^2)} \tag{12}$$

In *PMV* range between -0.5 and +0.5 the *PPD* varies from 0% to 10%

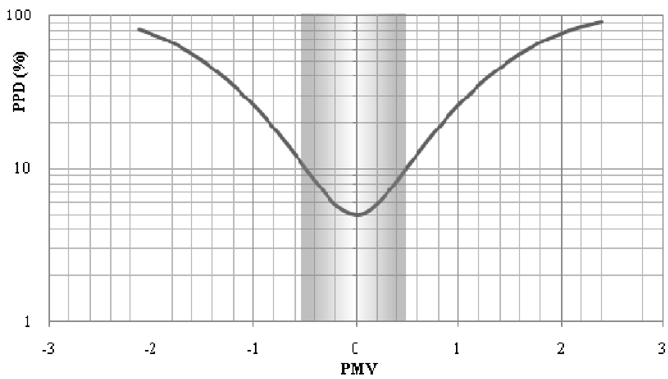


Fig. 1 – Relation "predicted percentage of dissatisfied – predicted mean value".

Last step it's to evaluate $\alpha_\Delta = \alpha^s - \alpha^i$ as viewed in first paragraph.

Table 3

PMV - Predicted Mean Vote

depends by											
M	W	t_a*	t_{mr}*	p_a		f_{cl}	h_c		t_{cl}		
fixed	fixed	adjustable	adjustable	depends by:	depends by:	depends by:	depends by:		depends by:		
0 [W/m^2]	0 [W/m^2]	thermal, isolation; air conditioning system	windows, places disposition	T	rh*	I_{cl}	v_{ar}		t_a	M,W	I_{cl}, f_{cl}, t_a
				not adjustable	adjustable	not adjustable	depends by	depends by	adjustable	fixed	←
				(Design Data)	e.g. air conditioning system	(Design Data)			←	←	
							v_a*	A_{DU}			
							adjustable	fixed			
							direction and velocity of air conditioned	e.g. 1.86 [m^2] (in average in Italy)			

4. Noise comfort

In a train, noises and mechanical vibrations are generated by the same source but the propagation is different. Noise is transmitted by air, while mechanical vibrations propagate through solid structures. Both are characterised by frequency and amplitude. Normally our ears work like a weighting filter, so the equivalent psychological impression induced by pure tones depends on the frequency. In this study, results of experiment conducted by Yamaguchi, Kato, Oimatsu & Saeki [9] have been revised to verify if a relationship between noise level and Comfort Index exists, while noise frequency are random.

During the experiment a group of people, everyone placed at the same distance from the noise source, was invited to indicate in a questionnaire their physiological impression in a scale from 1 to 7 (Table 4). Each five seconds the source produced a random frequency noise with a fixed level of decibels.

Table 4 - Psychological noise scale.

F_i	Impressions
1	very calm
2	quite calm
3	slightly calm
4	medium
5	slightly noisy
6	quite noisy
7	very noisy

The results was the frequency of index value (F_i) connected to noise level L(dB). So Yamaguchi, Kato, Oimatsu & Saeki drew seven statistic distributions (one for every index value). But if it draws a single graph taking into account the noise level connected at the peak frequency of index value the result is in Fig. 2.

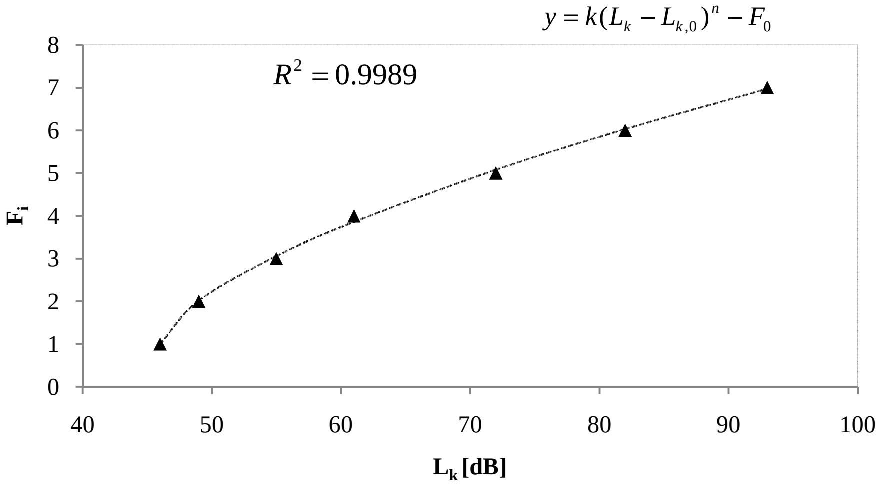


Fig. 2 – Relation "comfort index – noise level".

Applying the Stevens' Power Law [10], it's possible to hypothesize a relationship between the magnitude of a physical stimulus and its perceived intensity or strength.

$$\psi = k\varphi^n \tag{13}$$

Modifying the equation, adding the minimum threshold (46 dB) and the minimum index value ($F_i = 1$), the regression has a very good coefficient of correlation $R^2 = 0.9989$ (eq. 14; Fig. 2).

$$\begin{cases} F_i = k\left(L_k - L_{k,0}\right)^n - F_0 \\ k = 0.50; n = 0.64;\ L_{k,0} = 64\ dB;\ F_0 = 1 \end{cases} \tag{14}$$

At the end it's possible to estimate the management/design variables connected to the noise level, and evaluate the relative threshold as seen before. The variables identified are:

α_5: acoustic isolation;
α_6: train speed;
α_7: wheel defects;
α_8: rail defects;
α_9: twist index.

5. Vibration comfort

Many comfort indexes for vibration discomfort have been developed and proposed in scientific literature. Most of these usually connect physic stimulus with the acceleration transmitted to passengers' body. Also in this case, as in noise comfort, our sensations depend on amplitude and frequency. The acceleration has to be measured by accelerometers or predicted with a simulation analysis in three directions: along train motion (x-axis), vertical (z-axis) and transversal (y-axis). Then it's possible to evaluate comfort index using ISO 2631 [11] method. The three accelerations revealed, or predicted has to be weighted by a filter, then the root mean square values can be calculated as follows:

$$a_w^{r.m.s.} = \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} a_w^2 \, dt} \quad (15)$$

Then comfort index can be calculated as follows:

$$a = \sqrt{k_x a_{xw}^{r.m.s.2} + k_y a_{yw}^{r.m.s.2} + k_z a_{zw}^{r.m.s.2}} \quad (16)$$

Comfort Index thresholds, which has the dimension of an acceleration $[m/s^2]$, are: $a = [0; 0.53]$.
In this case many variables which influence acceleration are the same of noise vibration case, just because the source of vibration is the same. Variables individuated are:

α_{10}: dissipation system;
α_{11}: train speed;
α_{12}: wheel defects;
α_{13}: rail defects;
α_{14}: twist index.

The last step is to evaluate $\alpha_\Delta = \alpha^s - \alpha^i$ as viewed in the first paragraph.

6. Conclusions

Once all the variables and their respective thresholds are individuated, it's possible to define the hyper sphere in the $\mathbb{R}^{n+m}$ space and the global comfort vector associated to design or management problems. A consideration has to be done concerning human variables. Even if these variables have correlation with comfort, especially in case of thermal comfort, they are not considered as dimension of the hyper-sphere because they cannot be regulated (as seen in [3]). So these variables are considered as boundary conditions in thresholds computation, i.e. threshold have to be recalculated in every problem in dependency of: season, external temperature, external humidity; conditions which influences passengers' wearing apparel. Concerning noise comfort, even if the noise frequency is relevant in determination of passenger perception, experimental data demonstrates that it's possible to define a direct relationship between the comfort index and the waves' amplitude, if wave frequency varies randomly. Vibration comfort index and noise comfort index are not influenced by human factors. An exception has to be done in case of night sleeper trains; in which passengers lie in horizontal position therefore the vibration comfort index is modified.

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