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[N833] An Index for Motor Vehicle Passengers Acoustical Comfort

First Author: Federico Rossi

Università degli Studi di Perugia, Dipartimento di Ingegneria Industriale

Via G. Duranti 67, Perugia, Italy

Email address: frossi@unipg.it

Second Author: Andrea Nicolini

Università degli Studi di Perugia, Dipartimento di Ingegneria Industriale

Via G. Duranti 67, Perugia, Italy

Third Author: Mirko Filipponi

Università degli Studi di Perugia, Dipartimento di Ingegneria Industriale

Via G. Duranti 67, Perugia, Italy

ABSTRACT

Usually only noise equivalent levels are employed to individuate acoustical comfort for motor vehicle passengers [1]. However, noise levels do not take into account many other phenomena which may contribute to acoustical comfort such as insulation, speech intelligibility, engine noise hearing expectance and so on. An original vehicle comfort index (VCI) is here proposed which is obtained by a peculiar procedure: physical parameters (PP) such as noise equivalent level, statistical levels, STI index and vehicle acoustic insulation have been measured for different vehicles at several velocities. An arbitrary VCI scale has been introduced. VCI values for different comfort conditions have been determined by a jury test. Jury test has been led by adopting a S.A.O. (Statistical Average Observer) which was asked to judge vehicle acoustical comfort in terms of the proposed VCI scale. A relation between jury test results (experimental VCI) and PP has been introduced; thus, VCI may be evaluated by means of a measurement campaign for any condition.

KEYWORDS: Noise levels, Speech intelligibility, Vehicle passengers, Comfort index

INTRODUCTION

The paper deals with a new methodology to evaluate vehicle passengers acoustical comfort. The methodology introduces a psychophysical parameter named vehicle comfort index (VCI) which is supposed to depend on some measurable parameters. Motor vehicle internal noise is due to different sources [2]: i) exhaust duct noise; ii) engine and mechanical structures vibrations; iii) rolling tyres noise; iv) aerodynamic friction. Usually A-weighted noise equivalent level is the only parameter employed to describe passenger acoustical comfort. However, vehicle acoustical comfort is determined by other phenomena such as insulation, speech intelligibility, engine noise hearing expectance and so on. Therefore, it is supposed that vehicle acoustical comfort depends on other physical parameters (PP) such as statistical levels, STI index and vehicle body acoustic insulation. The proposed VCI is supposed to be obtained by a mathematical relation between such parameters. An experimental campaign has been carried out to measure PP by varying internal comfort conditions for two kinds of vehicles (a small car and a prestigious car). A VCI arbitrary scale has been proposed. An experimental campaign has been led to individuate VCI values for different vehicles and velocities by a jury test. A S.A.O. (Statistical Average Observer) constituted by 60 18-30 years old persons with no hearing diseases has been selected for jury test. By jury test results a relation between VCI and PP has been found.

1. ACOUSTICAL COMFORT FOR MOTOR VEHICLE PASSENGERS

Vehicle passengers optimum acoustical comfort is obtained by the following conditions:

1) low internal average noise due to i), ii), iii) and iv) sources;
2) no tonal (TC) and impulsive (IC) noise components;
3) low background noise;
4) low peak noise;
5) high speech intelligibility;
6) appropriate vehicle body sound insulation; sound insulation must be an optimum value in order to accomplish both noise insulation and meanwhile to allow passengers to hear alarm signals from the external environment and engine noise which is considered a driving feedback. Sound insulation varying between 30 and 35dB may be considered appropriate [2].

Acoustic comfort may be considered insensitive with respect to reverberation time because vehicle internal volume is a very small cavity which is characterized by very low reverberation times (less than 0.1s). Thus, VCI is supposed to depend on the following PP:

1) L_{Aeq}, A-weighted noise equivalent level;

2) presence or absence of TC and IC;
3) L_{90}, noise level exceeded for 90% of the measurement time [3];
4) L_{10}, noise level exceeded for 10% of the measurement time [3];
5) STI index [3];
6) R_w sound insulation index [4].

Thus, VCI may be expressed by the following relation:

$$VCI = F(L_{Aeq}, TC, IC, L_{90}, L_{10}, STI, R_w) \quad (1)$$

An experimental campaign has been led in order to individuate F function.

2. MEASUREMENT METHOD

A measurement campaign has been carried out to measure 1), 2), 3), 4), 5) and 6) PP by varying vehicle type and velocity. Measurement equipment is made up by: Bruel & Kjaer Investigator 2260 phonometer with Bruel & Kjaer model 4189 microphone for 1), 2), 3) and 4) parameters measurement; Symphonie data acquisition system by 01dB for 5) and 6) parameters measurement. Measurements have been carried out for two vehicle types each one belonging to a different vehicle class: A) Small cars; B) Prestigious cars.

Test vehicles are Fiat Punto 60S (A class) and Mercedes 200 CLK Elegance (B class). Measurements have been carried out with closed windows, four passengers on board (driver included) and air conditioning system off. Measurement conditions nomenclature is reported in Table 1.

Table 1: measurement conditions nomenclature

Vehicle	*Condition*							
	Velocity (km/h)							
	0	*20*	*40*	*60*	*80*	*100*	*120*	*140*
A	A1	A2	A3	A4	A5	A6	A7	
B	B1	B2	B3	B4	B5	B6	B7	B8

PP have been measured by the following method:

a) vehicle stopped and engine turned off for 6) parameter measurement;
b) 60s time interval for 1), 2), 3) and 4) parameters measurement;
c) measurement microphone placed near the passenger ears;
d) MLS sequence noise source placed in the back seat behind the passenger seat for 5)

parameter measurement;

e) parameter 2) has been measured according to Italian Normative [5];

f) parameter 6) has been measured according to ISO 717-1 [4].

An arbitrary scale has been proposed for VCI evaluation: VCI values belong to 0-10 range (0.1 step) where 0 and 10 VCI values correspond respectively to worst and best comfort conditions. A S.A.O. (Statistical Average Observer) has been selected in order to evaluate VCI values for each condition of Table 1. S.A.O. is constituted by 60 18-30 years old persons with no hearing diseases [6]. Each selected person hearing apparatus has been tested by means of an audiometric measurement campaign. Each person belonging to S.A.O. has been initially subjected to the extreme conditions B1 and A7 at which VCI is arbitrarily set respectively to 0 and 10. Then, each person has been asked to judge about the value which is to be associated to VCI for any other conditions of Tab.1. VCI judgement is demanded with 0.5 step in order to reduce judgement effort.

3. MEASUREMENT RESULTS

Measured PP are reported in Table 2 for Table 1 conditions.

Table 2: measured PP for Table 1 conditions

Condition	*Vehicle*	*Velocity (km/h)*	L_{Aeq} *(dBA)*	L_{90} *(dBA)*	L_{10} *(dBA)*	*STI*	R_w *(dB)*
A1	A	0	44.0	42.9	44.7	0.80	32
A2		20	55.4	54.4	56.4	0.75	
A3		40	61.0	59.5	61.9	0.71	
A4		60	63.7	62.8	64.5	0.67	
A5		80	68.8	67.5	70.2	0.61	
A6		100	72.2	71.2	73.0	0.55	
A7		120	74.4	73.4	75.3	0.51	
B1	B	0	42.4	41.5	43.1	0.91	33
B2		20	53.9	53.0	54.8	0.76	
B3		40	60.7	59.2	61.5	0.74	
B4		60	62.1	61.3	62.9	0.68	
B5		80	65.6	64.9	66.5	0.66	
B6		100	67.2	66.0	68.5	0.63	
B7		120	71.6	70.9	72.8	0.59	
B8		140	72.8	71.6	73.4	0.52	

Results shows that:

- TC and IC do not occur for each measurement condition. Thus, 2) parameter has not to be taken into account for VCI individuation (see Eq. (1));
- STI index decreases by increasing vehicle velocity (for each vehicle class);
- L_{Aeq}, L_{10} and L_{90} parameters increase with vehicle velocity (for each vehicle class);

Measurement results have allowed to individuate best and worst conditions which have been arbitrarily associated respectively to 10 and 0 VCI values (extreme conditions). Best condition is 0km/h for B vehicle class (B1 measurement condition, VCI=10). Worst condition is 120km/h for A vehicle class (A7 measurement condition, VCI=0).

Table 3: jury test results relative to A vehicle class

n. SAO	Measurement Condition							n. SAO	Measurement Condition						
	A1	A2	A3	A4	A5	A6	A7		A1	A2	A3	A4	A5	A6	A7
1	8.0	6.5	4.5	4.0	3.0	1.0	0.0	31	8.0	6.0	4.5	3.0	1.5	1.0	0.0
2	7.5	5.5	4.5	3.5	2.5	0.5	0.0	32	8.5	6.0	4.5	3.5	2.5	1.0	0.0
3	7.5	5.5	4.5	3.5	3.0	1.5	0.0	33	7.5	6.5	4.5	3.0	2.0	1.5	0.0
4	8.0	6.0	5.0	4.0	2.0	0.5	0.0	34	8.5	5.5	4.5	3.0	2.0	1.0	0.0
5	8.5	5.5	4.0	3.5	1.0	1.0	0.0	35	9.0	4.5	3.5	3.0	2.0	1.0	0.0
6	7.5	5.0	4.0	3.0	1.5	1.5	0.0	36	8.5	5.0	4.5	3.0	2.0	1.0	0.0
7	8.5	6.5	5.5	4.5	1.0	0.5	0.0	37	8.0	5.5	5.0	4.0	2.0	0.5	0.0
8	7.5	6.0	4.0	3.0	1.5	1.5	0.0	38	8.5	5.0	4.5	2.5	1.5	0.5	0.0
9	8.0	5.5	4.5	3.5	1.5	0.5	0.0	39	8.5	6.0	5.0	3.0	2.0	1.0	0.0
10	8.5	6.5	5.0	4.5	3.0	1.0	0.0	40	7.5	6.5	4.0	3.5	1.5	0.5	0.0
11	8.0	5.5	4.5	4.0	2.0	0.5	0.0	41	8.0	6.5	4.5	4.5	1.5	1.0	0.0
12	8.5	5.5	4.0	3.5	3.0	1.0	0.0	42	8.0	5.5	5.0	4.0	3.0	0.5	0.0
13	8.0	6.0	5.0	3.5	2.5	1.0	0.0	43	8.0	6.0	4.5	4.0	3.0	2.0	0.0
14	7.5	6.5	6.5	4.0	2.0	1.5	0.0	44	8.5	6.0	5.5	4.0	3.0	0.5	0.0
15	8.0	6.0	4.5	4.0	3.0	0.5	0.0	45	8.0	5.5	3.5	3.0	2.0	1.0	0.0
16	8.5	6.0	5.0	3.5	2.5	1.5	0.0	46	9.0	6.0	5.0	4.5	3.0	1.5	0.0
17	8.0	5.5	5.0	4.5	2.0	1.5	0.0	47	8.0	5.5	5.0	4.0	3.0	1.0	0.0
18	8.5	6.0	5.0	4.0	2.0	1.0	0.0	48	7.5	6.0	5.5	4.5	3.0	1.0	0.0
19	7.5	6.5	5.0	4.0	3.0	2.0	0.0	49	8.5	6.5	5.0	4.0	2.0	1.0	0.0
20	8.5	6.0	4.5	4.0	2.5	1.5	0.0	50	8.5	6.5	5.0	4.0	3.0	1.5	0.0
21	8.0	6.0	5.0	4.0	3.0	2.0	0.0	51	8.0	6.5	5.0	3.5	2.5	1.5	0.0
22	8.5	6.5	6.0	4.0	2.0	1.0	0.0	52	8.5	6.5	5.5	4.0	3.0	1.0	0.0
23	8.5	6.5	5.0	4.0	3.0	1.0	0.0	53	8.5	7.0	4.5	4.0	2.5	1.0	0.0
24	8.5	6.5	5.0	4.0	3.5	1.5	0.0	54	8.0	6.5	5.0	5.0	3.0	1.0	0.0
25	8.5	5.5	4.0	3.0	2.0	1.5	0.0	55	9.0	6.5	6.0	4.0	2.0	0.5	0.0
26	9.0	5.0	4.0	3.5	1.5	1.0	0.0	56	8.5	6.5	5.0	5.0	2.5	1.0	0.0
27	8.5	6.5	4.5	3.5	2.0	1.0	0.0	57	9.0	5.5	3.0	3.0	2.5	1.0	0.0
28	7.5	5.0	4.5	3.0	1.0	1.0	0.0	58	8.5	6.5	6.0	4.0	2.5	1.0	0.0
29	8.5	5.5	5.0	5.0	2.0	1.0	0.0	59	8.0	5.5	5.0	4.5	3.0	0.5	0.0
30	8.5	6.5	5.5	4.0	2.0	2.0	0.0	60	8.5	4.5	4.5	3.5	2.0	1.0	0.0

VCI values by jury test relative to Table 1 measurement conditions are reported in Tables 3 and 4. Average jury test results are reported in Table 5 (experimental VCI).

Table 4: jury test results relative to B vehicle class

n. SAO	Measurement Condition								n. SAO	Measurement Condition							
	B1	B2	B3	B4	B5	B6	B7	B8		B1	B2	B3	B4	B5	B6	B7	B8
1	10.0	6.5	5.0	4.0	4.0	3.0	1.5	0.5	31	10.0	8.5	7.5	7.0	7.0	6.0	4.5	4.5
2	10.0	6.5	4.5	4.5	3.5	2.5	1.5	0.0	32	10.0	8.5	8.0	7.0	7.5	6.5	5.5	5.5
3	10.0	6.0	5.0	4.0	3.5	3.5	2.5	1.0	33	10.0	6.0	5.0	4.0	3.0	3.0	1.5	1.0
4	10.0	6.5	5.5	4.0	4.0	2.5	2.0	0.0	34	10.0	6.0	5.5	4.0	3.5	3.5	2.5	0.5
5	10.0	6.5	5.5	4.0	2.0	2.0	1.0	1.0	35	10.0	6.5	5.5	4.0	3.0	3.0	1.5	0.5
6	10.0	6.0	5.0	4.0	3.0	2.5	1.5	1.0	36	10.0	5.5	5.0	4.0	3.0	2.0	1.0	0.0
7	10.0	7.5	6.5	5.0	3.0	2.0	0.5	0.5	37	10.0	6.0	4.5	3.0	3.0	2.0	1.0	0.0
8	10.0	6.5	5.5	3.0	3.0	2.5	1.5	1.0	38	10.0	5.5	5.0	4.5	3.0	2.0	1.5	0.5
9	10.0	6.0	5.5	4.0	3.5	3.0	1.0	0.0	39	10.0	6.0	5.5	5.0	3.5	2.0	1.0	0.0
10	10.0	7.0	5.0	4.5	3.0	3.0	1.0	1.0	40	10.0	6.0	4.5	3.5	2.0	1.5	1.0	0.5
11	10.0	5.5	5.0	4.0	2.5	2.5	1.0	0.5	41	10.0	6.0	5.0	4.0	3.0	2.5	2.0	1.0
12	10.0	6.0	4.0	4.0	3.0	3.0	2.0	0.5	42	10.0	6.5	5.5	4.0	3.0	2.0	1.0	0.0
13	10.0	7.0	5.0	4.5	3.5	3.0	2.5	1.0	43	10.0	6.5	5.5	4.5	3.0	2.0	1.0	0.0
14	10.0	6.5	6.5	5.0	2.5	2.5	1.5	1.0	44	10.0	6.5	5.5	5.0	3.0	3.0	2.0	0.0
15	10.0	6.0	5.5	4.0	3.5	3.0	1.5	0.0	45	10.0	6.5	5.5	4.0	4.0	3.5	2.0	1.0
16	10.0	7.0	5.0	4.5	3.5	3.5	1.5	1.0	46	10.0	7.0	6.0	5.0	3.0	3.0	1.5	0.0
17	10.0	6.0	5.5	5.0	3.5	3.0	1.5	0.5	47	10.0	7.0	5.0	3.5	3.0	3.0	2.0	1.0
18	10.0	7.0	5.5	4.5	3.0	2.5	1.5	1.0	48	10.0	6.0	5.5	5.0	4.0	3.5	2.5	1.5
19	10.0	6.5	6.0	4.5	4.0	4.0	2.0	1.0	49	10.0	6.5	5.5	4.0	4.0	3.0	2.5	0.5
20	10.0	6.5	5.0	4.5	4.0	3.5	1.5	1.0	50	10.0	6.5	5.5	4.5	4.5	3.5	2.0	0.5
21	10.0	7.0	5.5	4.5	4.0	3.0	2.5	1.5	51	10.0	7.0	6.5	5.0	4.0	3.5	2.0	0.0
22	10.0	7.0	6.5	4.5	3.0	3.0	1.0	0.0	52	10.0	6.5	5.5	4.5	3.5	3.0	1.5	0.5
23	10.0	6.5	5.5	4.5	3.5	3.0	1.5	1.0	53	10.0	6.5	5.5	4.5	3.0	3.5	1.5	0.5
24	10.0	7.0	5.5	4.5	4.0	3.5	2.5	1.0	54	10.0	6.5	5.5	4.5	4.0	4.0	2.0	0.5
25	10.0	6.0	4.5	4.0	3.0	2.0	1.5	1.0	55	10.0	7.0	5.5	4.5	4.0	3.5	1.5	0.5
26	10.0	6.5	5.0	4.0	3.5	2.5	1.5	0.5	56	10.0	6.5	6.5	5.0	4.5	3.0	2.5	0.5
27	10.0	6.5	4.5	4.0	3.0	2.0	1.5	0.5	57	10.0	7.0	6.5	6.0	4.0	3.5	1.0	0.0
28	10.0	6.0	5.0	4.5	3.0	2.0	1.0	0.0	58	10.0	7.0	6.5	5.0	3.5	3.0	1.5	1.0
29	10.0	6.5	5.5	5.0	3.0	2.5	1.0	0.0	59	10.0	7.0	4.5	3.0	3.5	3.5	1.5	0.5
30	10.0	6.5	5.5	4.5	4.0	4.0	2.0	0.0	60	10.0	6.5	6.0	4.0	4.0	3.5	2.0	1.0

Jury test average results have been correlated with the measured PP relative to the same vehicle class-velocity configuration. Correlation have allowed to individuate the relation between VCI and PP (see Eq. (1)). It is supposed that VCI depends on each PP by the following linear relation:

$$VCI = a \cdot L_{Aeq} + b \cdot L_{90} + c \cdot L_{10} + d \cdot STI + e \cdot R_w \qquad (2)$$

A linear regression procedure has been used to calculate Eq. (2) constants: a=−0.047, b=−0.030, c=−0.052, d=14.518, e=0.069. VCI values obtained by Eq.(2) relatively to Table 1 conditions are reported in Table 5 (estimated VCI). The proposed relation shows that: VCI decreases when noise levels (L_{Aeq}, L_{90} and L_{10}) increase (a, b and c are negative); VCI reduction is more sensitive to L_{10} values because vehicle passenger is highly affected by peak noise (|c|>|a|>|b|); VCI reduction is less sensitive to L_{90} values because vehicle passenger hearing apparatus gets used to background noise (|c|>|a|>|b|); VCI increases when speech intelligibility (STI) increase (d is positive).

Table 5: Average jury test results

Measurement Condition	*Vehicle*	*Velocity (km/h)*	*Experimental VCI values*	*Experimental VCI variance*	*Estimated VCI values*
A1	A	0	8.2	0.2	8.1
A2		20	5.9	0.3	5.9
A3		40	4.8	0.4	4.6
A4		60	3.8	0.3	3.7
A5		80	2.3	0.4	2.4
A6		100	1.1	0.2	0.9
A7		120	0.0	0.0	0.0
B1	B	0	10.0	0.0	10.0
B2		20	6.4	0.2	6.3
B3		40	5.4	0.3	5.2
B4		60	4.3	0.3	4.1
B5		80	3.4	0.3	3.4
B6		100	2.9	0.4	2.9
B7		120	1.5	0.2	1.7
B8		140	0.6	0.2	0.5

CONCLUSIONS

A new methodology to determine acoustical comfort for motor vehicle passengers has been proposed. Physical parameters (PP) such as noise equivalent level, statistical levels, STI index and car body sound insulation have been measured by varying velocity and vehicle type. An arbitrary psychophysical parameter scale (Vehicle Comfort Index, VCI) has been introduced.

VCI values equal to 0 and 10 have been arbitrarily associated to worst and best comfort conditions which correspond respectively to 120km/h velocity for a small car and 0km/h velocity for a prestigious car. VCI values for two vehicle types at different velocity conditions have been evaluated by means of a jury test. A linear relation between VCI and PP has been found. A development of the proposed methodology is planned which concerns on:

- the verification of the proposed relation by a consistence test;
- the individuation of a more accurate relation by testing other vehicles types and taking into account other PP.

SYMBOLS

Symbols	*Units*	*Description*
a	adimensional	VCI model constant (VCI versus L_{Aeq})
b	adimensional	VCI model constant (VCI versus L_{90})
c	adimensional	VCI model constant (VCI versus L_{10})
d	adimensional	VCI model constant (VCI versus STI)
e	adimensional	VCI model constant (VCI versus R_w)
L_{Aeq}	dBA	Equivalent continuous A-weighted sound pressure level
L_{10}	dBA	Noise level exceeded 10% of the measurement time
L_{90}	dBA	Noise level exceeded 90% of the measurement time
R_w	dB	Sound insulation index
STI	adimensional	Speech transmission index
VCI	adimensional	Vehicle comfort index

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