Energy Performance Optimization of a Bus for Urban Public Transport

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Abstract— **Nowadays many people use public transports in urban centres. Consequently, every day a lot of buses move within cities, trying to ensure the best service to citizens. During the year buses become crowded places and using an air conditioning system in constant operation, it tries to ensure a certain condition of comfort for the passengers on board. The aim of this study is to analyse and optimize the energy performance of a bus shell, identifying practical solutions that have not yet been adopted in order to reduce the impact of air conditioning on bus consumption and, therefore, on air pollution. For this reason it was decided to conduct a thermal analysis of a bus for public transport, in order to understand the behaviour of the bus shell and to deduce possible optimization measures that have not yet been made until now. The analysis was carried out considering the hottest day of July and the coldest day of January, considering the conditions of operation based on the most common graphics TGM able to define the concentration of traffic city during the 24 hours per day. The study was done using the dynamic simulation software TRNSYS. With this software it was possible to recreate faithfully the structure of the bus and the external environmental conditions, assessing the impact of different technical solutions for an improvement of internal conditions and a reduction of the cooling capacity required. Because the presence of passengers in public transport is considered like a "benefit" during the winter, the analysis started with the identification of a summer solution and the subsequent evaluation of this solution for the wintertime. The aim of this study was to optimize the bus shell and select the most appropriate solutions. Regarding the transparent surfaces it has been given importance to factors such as the thermal transmittance and the solar gain factor (g-value). Aware of the influence given by the solar radiation on the energy loads, we have simulated bus energy performance also considering different types of paintwork with high reflectance.**

I. INTRODUCTION

Nowadays a lot of people spend many hours during the day using public transport. Traffic conditions in Rome necessarily require the frequent use of public buses. In Italy conditioning the public transport arises from the need to improve the comfort of people who daily use public services moving around the city. Internal temperature and humidity conditions are important factors in terms of passengers comfort and health. For this reason, the automobile industry has recently developed the thermal comfort issue which have to take care of both the health of the passengers and the driver. The problem connected with the comfort onboard is very complex because, inside, there are strong gradients of air velocity and temperature. Moreover the solar radiation inside the vehicle, especially during the summer, is very important [1]. In this study it has been developed a model applying dynamic simulation software TRNSYS (already largely used to analyze the thermal exchanges [2]-[5]). In order to give a better understanding of energy behavior of the bus shell, the identification of practical solutions that have not been used yet, the improvement of the isolation from the outside and the limitation of the power required for cooling the cabin have been carried out.

II. MODELLING

The analysis was carried out considering a generic model of a bus and its geometrical characteristics are shown in Fig. 1. The vehicle stratigraphy is given in Table II and III. To provide the thermal analysis the dynamic simulation software TRNSYS has been used. Through this programme it was possible to faithfully reproduce both the geometry of the bus and the external environmental conditions: the bus modelling is done through the TRNSYS Build, which is the section of the software that allows to generate the vehicle's model only. The connection of the "build" with the outside world is possible by using the TRNSYS Studio, through which it is possible to connect specific types, generating a pattern of interconnection (Fig. 2).

A. *Trnsys Build*

Geometry of the vehicle (Fig. 1) and stratigraphy have been inserted through TRNSYS Build. The materials used into the model are shown in Table II and III. Considering the initial configuration of the vehicle (called "standard configuration") it was used a single glass and its characteristics are reported in Table IV. The solar absorption coefficient of the blue paint, commonly adopted for buses, was considered to be equal to 0.6 [6]. Moreover, the model was oriented to have the larger surfaces exposed to the south and north respectively, and it was considered a variable number of passengers on board, Table I [7]. Having knowledge that TRNSYS is always connected with the energy performance of buildings, it was generated a model which is the nearest to the operating conditions of a city bus. With this aim, they were appropriately used convective coefficients that could simulate the relative motion of the air in the model, in order to simulate the bus movement [8]. In this way it was possible to vary the convective coefficients considering the bus motion [9].

Surfaces	[m2]
Lateral walls	32.3
Orizzontal walls	26.15 + 26.15
Trasparent	31

Fig. 1. Bus model

TABLE I
Daily Passengers on Board

Step time	Passengers on board	Step time	Passengers on board
6:00	20	15:00	40
7:00	80	16:00	40
8:00	80	17:00	80
9:00	40	18:00	80
10:00	40	19:00	40
11:00	40	20:00	40
12:00	40	21:00	40
13:00	80	22:00	20
14:00	40	23:00	1

TABLE II
Characteristics of Vertical Opaque Walls

Material	Thickness [mm]	Density [kg/m^3]	Conductivity [kJ/h m K]	Heat Capacity [kJ/kg K]	Resistivity [hm^{2}K/kJ]
Fiberglass	8	2500	0.7920	1.256	
Air					0.034
Fiberglass	8	2500	0.7920	1.256	

TABLE III
Characteristics of Horizontal Opaque Walls

Material	Thickness [mm]	Density [kg/m^3]	Conductivity [kJ/h m K]	Heat Capacity [kJ/kg K]	Resistivity [hm^{2}K/kJ]
Fiberglass	8	2500	0.7920	1.256	
Wood panel	20	350	0.36	1.88	
Air					0.034
Fiberglass	8	2500	0.7920	1.256	

TABLE IV
Characteristics of Transparent Walls

Material	Thickness [mm]	Transmittance [W/m^2 K]	g-value
Glass	8	5.68	0.855

B. Trnsys Studio

The model connection with the outside world is made through the TRNSYS Studio. Fig. 2 allows to see how the software uses external data-sheet (Type RH/T), entering values of relative humidity and ambient temperature. In this way the direct use of weather-data - that contains airport meteorological-data - hasn't been applied and this because it is not always correct to simulate the external weather conditions. Despite this, the weather-data (Type 109-TMY2) were still considered to use information relating to solar radiation. Type33e receives as input relative humidity values and ambient temperature values to calculate the dew point temperature. Type69b calculates the fictive sky temperature. Calculators, represented in Fig. 2, allow to perform mathematical operations between data contained in different types. Type56a - representing the model and using the generated one through TRNSYS Build –

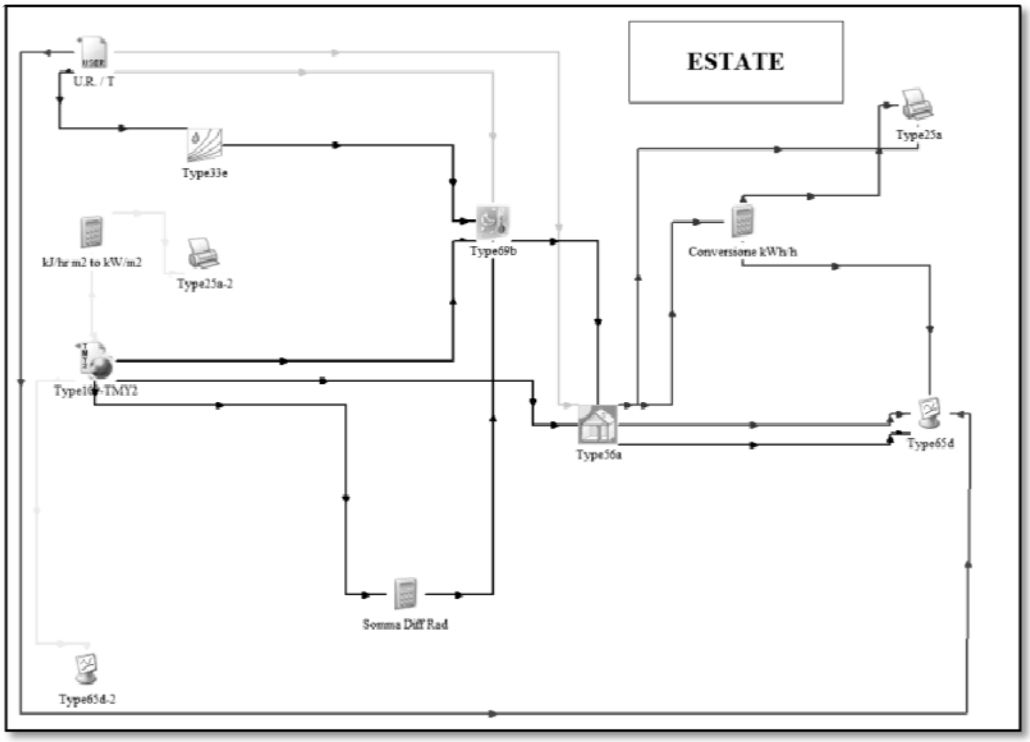

Fig. 2. TRNSYS Studio piping

allows to create a connection with the "outside world." Finally, Type65d graphically displays the thermal loads and Type25a allows to get a spread sheet with data related to loads, calculated hour by hour. Referring to critical conditions, the analysis was performed by reproducing the environmental conditions in summer and winter: more in depth, it was considered July 13th and January 11th. The choice to use a dynamic software, such as TRNSYS, to simulate the energy performance of a bus shell is connected with the high reliability and effectiveness of the software analysis. The higher level of detail achievable is related to the possibility of taking into account the realistic temperature fluctuations and, therefore, a more realistic calculation of the energy loads. The steps of the analysis are shown in Fig. 3.

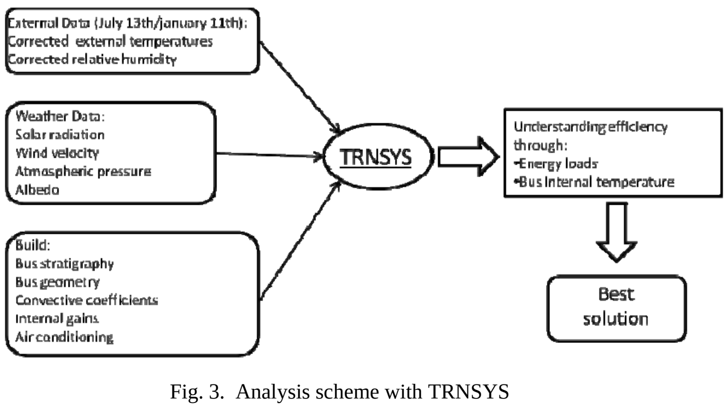

Fig. 3. Analysis scheme with TRNSYS

III. BUS SHELL EFFICIENCY EVALUATION

An air conditioning system (hot / cold) - characterized by infinite power and set-point temperatures of 27°C for the summer and 20°C for the winter - has been considered to evaluate the shell efficiency.

Starting from the analysis of this configuration, simulations have been performed according to the following steps:

Summer

- Intervention on transparent surfaces
- Intervention on opaque surfaces
- Intervention on colours
- SUMMER OPTIMAL SOLUTION

Winter

- Checking the summer optimal solution

The first step is based on the energy behaviour analysis, improving the technical characteristics of the glass. The characteristics that we focused on are:

- the thermal transmittance value;
- the value of the solar gain factor (g-value).

Following the first step, which is not change the stratigraphy of the opaque walls and acts on transparent surfaces only, it was analysed the vehicle's behaviour by adopting for the summer period (July 13th) windows shown in Table V.

TABLE V
Technical Characteristics of Used Glasses

	Material	Thickness [mm]	Transmittance [W/m^2 K]	g-value
Glass type 2	Double glazing	4/16/4	2.83	0.755
Glass type 3	Float Glass	19	5.16	0.682
Glass type 4	Double glazing	4/16/4	0.98	0.440

Obtained the best results, it was performed the second type of intervention changing only the opaque walls. In this second step, it was interposed between the fiberglass panels a polyurethane foam, its characteristics are shown in Table VI. Different simulations were performed - considering 1 cm, 2 cm and 3 cm of foam – waiting for a power request reduction.

TABLE VI
Technical Features of the Thermal Insulation

Material	Density [kg/m^3]	Conductivity [kJ/h m K]	Heat Capacity [kJ/kg K]
Polyurethane Foam	33	0.023	1.674

Using the foam insulation, it was obtained a reduction of the opaque walls thermal transmittance as reported in Table VII. Regarding the horizontal walls, 1 cm of foam has been incorporated into stratigraphy, getting a thermal transmittance value of 1.208 W/m^{2}K, which has been compared to 1.941 W/m^{2}K related to standard configuration.

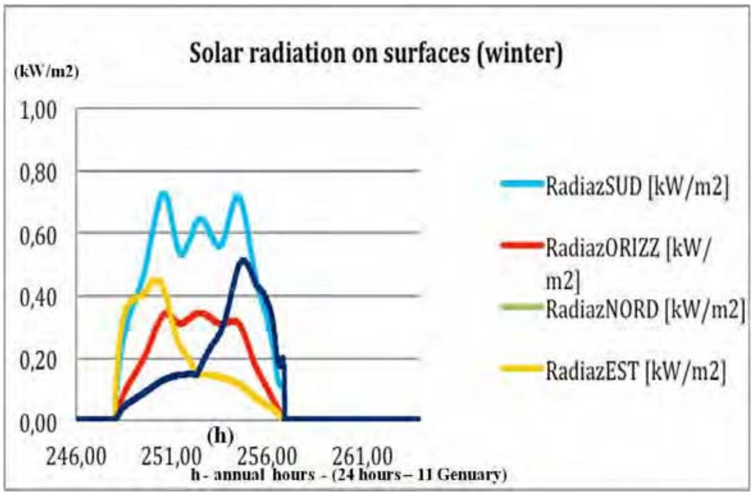

Fig. 4 - Solar radiation on surfaces (winter)

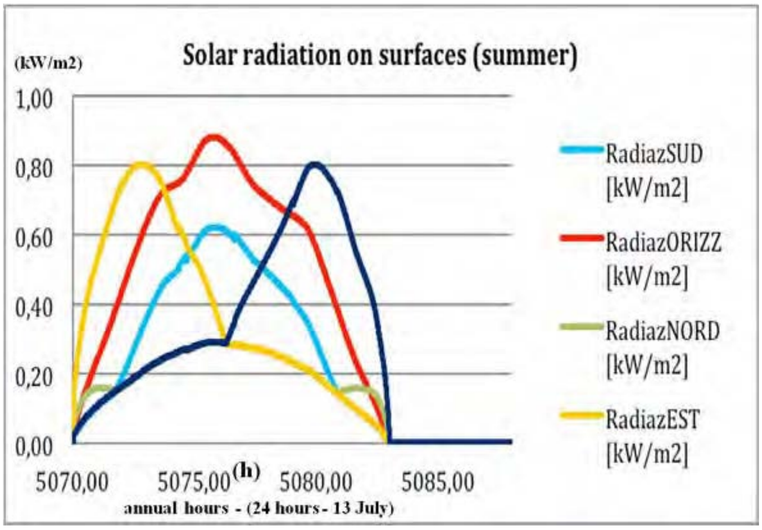

Fig. 5 - Solar radiation on surfaces (summer)

TABLE VII
Insulation Thickness and Walls Overall Transmittance

Polyurethane Foam (vertical walls)	Insulation thickness [mm]	Entire wall Transmittance [W/m^2 K]
Standard_wall	0	2.739
Wall_10	10	1.476
Wall_20	20	0.899
Wall_30	30	0.646

Before the comparison between different solutions, it was analyzed the solar radiation and ambient temperature along the 18 hours per day (both summer and winter). In this way it was possible to understand which is the most critical time interval. The results are shown in Figs. 4, 5 and Figs. 6 and 7.

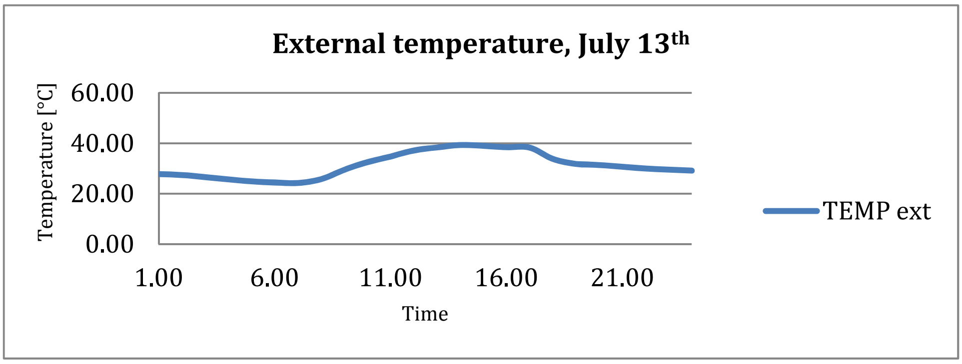

Fig. 6 - External temperature, July 13th

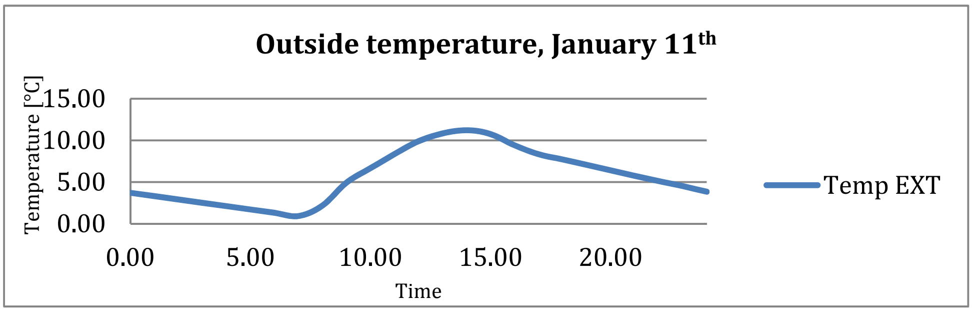

Fig. 7 - External temperature, January 11th

IV. SUMMER RESULTS

Starting from the standard configuration, there were applied the following steps:

- Intervention on transparent surfaces
- Intervention on opaque surfaces
- Intervention on colours
- SUMMER OPTIMAL SOLUTION

A. *Intervention on Transparent Surfaces*

Referring to the first step, it has been performed the comparison between the bus standard configuration (standard glass) and the types of glasses shown in Table V, adopting a value of solar absorbance of 0.6 for opaque surfaces. Adopting glasses with high performance, it has been obtained the results shown in Fig. 8, that show the daily service thermal load (sum of thermal loads calculated hour by hour).

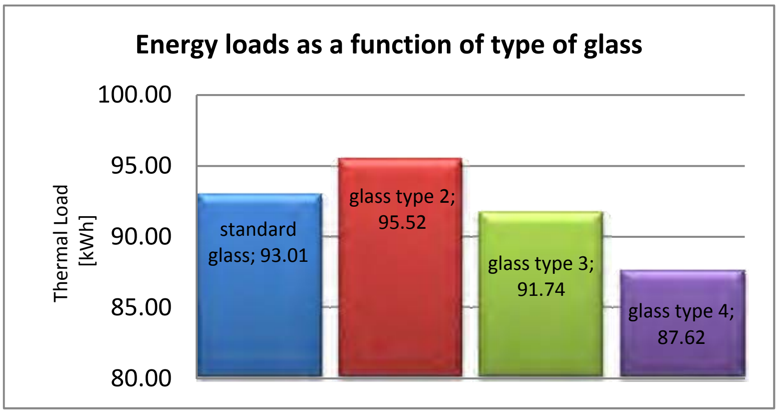

Fig. 8 – Energy loads as a function of type of glass

Table VIII shows the differences between standard configuration of the bus and the different type of glasses used (referring to a single work-day).

TABLE VIII
Percentage Difference Between Thermal Loads

Glass Type	Thermal load [kWh]	Percentage difference [%]
Standard glass	93.01	-
Glass type 2	95.52	2.70
Glass type 3	91.74	-1.36
Glass type 4	87.62	-5.79

B. Intervention on Opaque Surfaces

It was made the comparison between the bus standard configuration (stratigraphy of opaque walls shown in Table IV) and the new configuration in which the polyurethane foam (as a thermal insulator) has been considered. The simulations have been performed using 1 cm, 2 cm and 3 cm of foam within the opaque walls. Fig. 9 shows the results carried out.

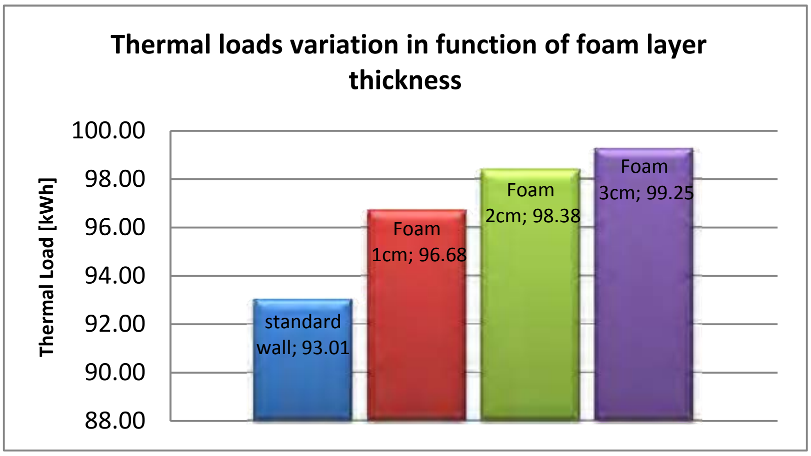

Fig. 9 – Thermal loads variation as a function of foam layer thickness

Fig. 9 points out that, using the foam, there is an increase of thermal loads. Therefore, it is clear that this intervention cannot be considered suitable to optimize the energy performance of the bus shell.

C. Intervention on Colours

The last phase of the analysis involves the use of paints characterized by a reduced solar absorption factor (light colours). Thermal loads were calculated by considering at the beginning classic blue paint colour (characterized by a solar absorbance of 0.6) and then a white paint (characterized by solar absorbance equal to 0.14). The colour's effects on thermal loads are shown in Fig. 10. There is a difference between the two solutions and it is equal to 10.65%.

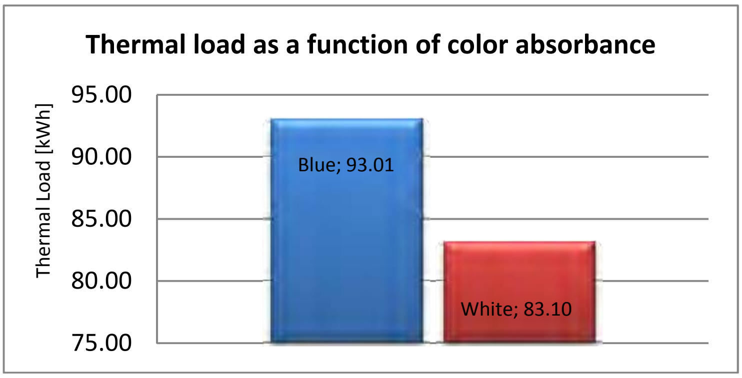

Fig. 10 - Thermal load as a function of colour absorbance

The Fig. 10 shows the difference between conventional paints and white paints. A thermal loads reduction equal to 10.65% is associated to the use of a high-reflective paint.

V. DISCUSSION

In order to optimize its energy performance and to reduce the energy request in summer, some interventions on the bus shell have been done. The changes are:

- the use of high performance glasses, compared to conventional single glasses (thickness of 4 mm);

- the use of an insulating foam;
- the use of a paint with high reflectance (white paint).

Using the Glass type 2 - double glaze characterized by a lower thermal transmittance value - there is a thermal load increase. This is connected with the lower value of the thermal transmittance of the glass and this produces a heat accumulation inside the bus shell. These considerations can be better understood by considering the basic equation that defines the cooling load [5].

$$Q_{cool} = (Q_{sol} + Q_{\text{int}}) - \eta_u (Q_{disp} + Q_{vent}) \quad (1)$$

In the Eq. (1) the terms related to the internal gains and ventilation are constants. Using Glass type 2 there is a variation connected only with the heat losses. The solar gains are unchanged and the total cooling load reach higher values.

Using the Glass type 3 - single glass characterized by a high thermal transmittance and a g-value smaller than the standard glass it is possible to assess a load reduction. The importance of the g-value is due to the meaning of the solar gain factor, which can be defined as the sum of two parameters: an optical component and a thermal component. The optical component takes the name from the optical transmittance while the thermal component from the emissivity of the inner side (proportional to the optical-absorbance). The solar radiation between 300 nm and 2500 nm absorbed by the external side of the window is released through the internal side with a longer wavelengths (medium infrared and far infrared), in the form of heat. Referring to the equation (1), which expresses the cooling load, it is possible to assess that using Glass type 3 a reduction of the solar gains, connected with the lower g-value, and the thermal dispersion, Q_{disp}, that is the same to the standard configuration, has been recorded.

Using the Glass type 4 - glass that has the lowest thermal transmittance and the lowest g-value – it was obtained a thermal heat load lower than the standard configuration's value. Using a glass with these characteristics, the decrease energy demand can be correlated to a simultaneous reduction of the solar gains (Q_{sol}) and of the shell dispersion capacity (Q_{disp}) . In this case the transmittance is more effective than the solar gain factor.

The effect of insulating foam, placed between the opaque surfaces, represents an incorrect choice to optimize the shell's performances during summer. Referring, once again, to the Eq.(1), it is possible to assert that the presence of a thermal insulator leads to a lower thermal flows dispersion with a consequent increase of the load itself.

The last intervention is characterized by the application of a high reflective paint. The white colour has a solar absorbance of 0.14 and it allows a greater solar radiation reflection compared to the conventional paints today used.

VI. SIMULTANEOUS EFFECTS

Analysing the simultaneous benefits using glasses and colours with high features, it was performed a simulation using both the glass type 4 and the white paint. It is clear why we haven't taken in account the use of the insulating foam.

The results, compared with the standard configuration of the bus, are shown in Fig. 11.

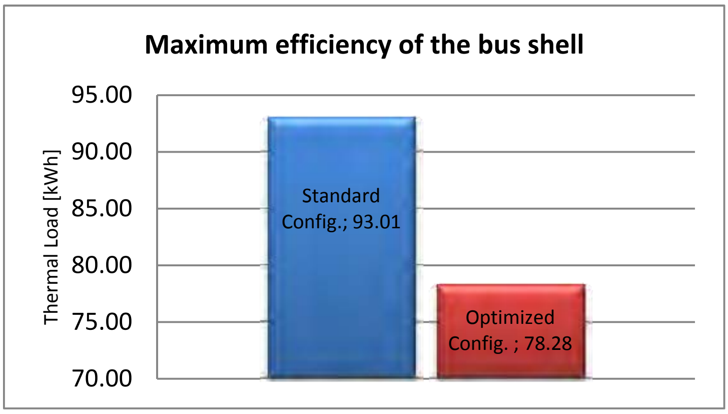

Fig. 11 – Benefits associated with the simultaneous use of high performance glazing and high-reflectance paint

The thermal load reduction compared with the starting configuration of the vehicle is equal to 15.84%.

Because of a bus use during the whole year, it was also performed a simulation in winter conditions, considering the optimized shell (white paint and glass type 4). The results obtained during the coldest day of January (January 11th) and compared with the standard configuration of the vehicle, are shown in Fig. 12 and Fig. 13.

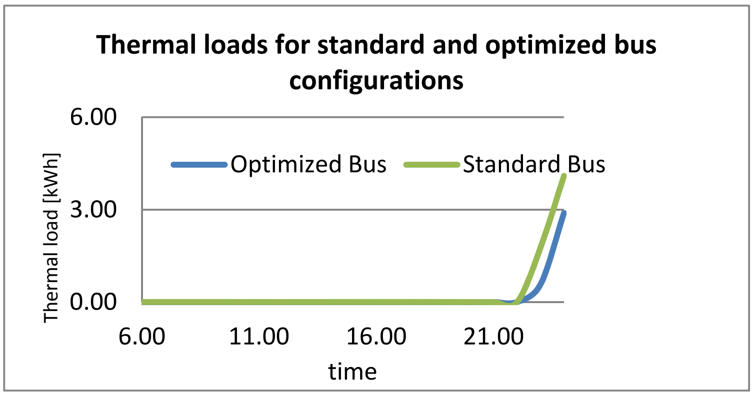

Fig. 12 - Thermal loads for standard and optimized bus configurations

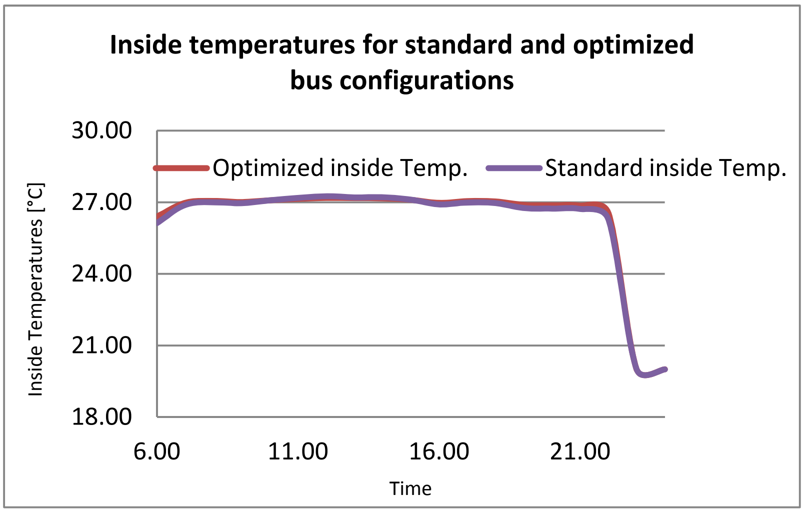

Fig. 13 - Inside temperatures for standard and optimized bus configurations

Figs. 12 and 13 show as the optimization procedure implies a reduction of the thermal load, while the internal temperature remains substantially unchanged in the two cases. The air conditioning system is used only during the last hours of the daily service, however, it is possible to assess a load reduction.

Considering the bus engine power - from 245 HP to 290 HP [10] - and a bus weight of 12080 kg, it was analysed the power/weight ratio concerning the use of the glass type 4. Using a double-glazing instead of a conventional glass means an increase of vehicle's weight. The specific weight of the glass and the weight/power ratio are shown in Table IX. Using the glass type 4, there is an increase of the bus weight of approximately 310 kg. For this reason the total weight of the bus is equal to 12390 kg, Table IX, and it was used to calculate the weight/power ratio for an engine with 245 hp and 290 hp.

TABLE IX
Analysis of the Weight / Power Ratio

	Single weight	Transparent surface	Total weight
Standard config. bus	12080 kg		
Glass type 4	20 kg/m^2	31 m^2	620 kg
Standard glass	10 kg/m^2	31 m^2	310 kg
Bus with standard glass			12080 kg
Bus with glass type 4			12390 kg

Engine power	245 CV	290 CV	
Standard config. bus	49.3 kg/CV	41.65 kg/CV	
Optimized config. bus	50.6 kg/CV	42.72 kg/CV	
Engine efficiency	0.35		
Alternator efficiency	0.9		
Air conditioning efficiency	3		
Diesel cost	1.67 €/liter [11]		

Using data shown in Table IX, a fuel annual saving of 20% has been estimated. Considering the fleet of vehicles which is owned by a public transportation company, it is possible to reach high economic savings.

It is important to observe that an annual saving - in terms of liters of fuel - can involve a reduction of CO2 emissions into the environment. Being aware of the influence of CO2 on the greenhouse effect, optimizing the bus with the proposed solutions and lowering the fuel consumption, the reduction of CO2 was estimated. This value is approximately equal to 1464 kg/year per bus.

VII. Preliminary Analysis of the Construction Cost

A cost analysis associated to the use of glass type 4 has been joined to the energetic analysis. Considering a transparent surface of 31 m^2 and an estimated price of glass of 140.00 €/m^2, the additional cost for each bus is 4340.00 Euros. Estimating a standard bus price of 150000.00 Euros, it is possible to state that using glass type 4 a surplus of the starting amount of about 3% has been recorded (Table X). This analysis should be considered as a preliminary one because it was not taken into account the relationship between the bus producer and the manufacturer of insulating glass units. The relationship between bus manufacturers and glasses producer should lead to a cost reduction of vehicle's production. In this costs analysis was not considered the use of high reflectance paint because it is already included into the global bus cost.

TABLE X
Efficiency Costs Analysis

	Unit cost	Transparent surface	Global cost
Standard config. bus	150000,00 €		150000.00 €
Glass type 4	140.00 €/M^2	31 m^2	4340.00 €
Total			154340.00 €
Surplus			≅3 %

VIII. Conclusions

Today many people use public transport and it is important to improve the bus comfort, especially in critical conditions such as rush hours and summer time. For this reason it is important to improve energy performances of a bus shell, under critical conditions, such as summer weather (high temperatures) and maximum number of passengers on board. There were evaluated, through a dynamic simulator, several interventions, such as using more efficient glasses and paints characterized by a low solar absorbance value. In order to reduce the thermal loads, it is possible to improve the energy performances of vehicles adopting a glass characterized by a thermal transmittance value equal to 0.98 W/m^2K and a solar gain factor equal to 0.44 (specifications glass type 4). Moreover, they have been calculated the thermal loads by adopting a high reflectance paint (white color) and the benefit of both solutions - in terms of energy demand - equal to 15.84% has been evaluated.

The shell optimization allows to adopt interventions that can be considered suitable also during the winter.

Aiming to achieve the global efficiency of the bus shell, it was estimated the cost of a conventional bus. Then it was evaluated the cost of a glass (per square meter) having the same performances of the glass type 4 used in the simulations. The preliminary costs analysis leads to a price's increase of about 3%, but it brings, at the same time, to an annual fuel saving of 20% for the diesel vehicle.

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